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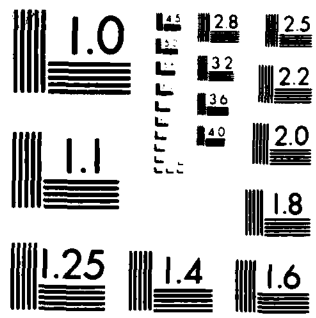

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HEAT RECOVERY FROM KETENE GAS COOLDOWN

AD-A142 821

LARRY E. WOLVERTON

HOLSTON ARMY AMMUNITION PLANT
HOLSTON DEFENSE CORPORATION
KINGSPORT, TENNESSEE 37660

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U.S. ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER

LARGE CALIBER WEAPON SYSTEMS LABORATORY

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18. SUPPLEMENTARY NOTES

This project was accomplished as part of the U.S. Army's Manufacturing Methods and Technology Program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel. (cont)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Energy conservation	MMT-Energy conservation
Ketene gas	Gas-to-gas heat exchanger
Acetic anhydride	Ketene cracking furnace
RDX	Waste heat recovery
HMX	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A gas-to-gas heat exchanger was installed to recover a portion of the heat from the ketene vapor stream leaving a cracking furnace to preheat the combustion air. Results of the evaluation indicated that combustion air temperature increased an average of 344°C. The final temperature of the ketene gas leaving the heat exchanger averaged 467°C and never dropped to the critical 350°C temperature at which recombination of the ketene/water and conversion to acetic acid occurs. There was no significant fouling inside the heat exchanger tube (cont)

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20. ABSTRACT (cont)

bundle and the rate and quality of crude acetic anhydride production were not affected. The amount of combustion air supplied to the furnace burners was about half the theoretical amount because of the draft air introduced to the furnace. Economic evaluation shows that the profitability index and payback period at the current production level is insufficient to justify the expense of installing the heat recovery systems on all the ketene cracking furnaces.

18. SUPPLEMENTARY NOTES (cont)

S. Moy, Energetic Systems Processing Division, is the project engineer and coordinator for this project.

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INTRODUCTION

High energy costs make it essential that energy resources be managed carefully and with economy to achieve cost effective chemical plant operation - an objective for Holston Army Ammunition Plant (HSAAP) that is shared by the management of Holston Defense Corporation (HDC) and the Department of the Army. In pursuit of this objective HDC actively participated in an energy management study conducted at HSAAP in August 1975 by consultants from DuPont's Applied Technology Division. The purpose of the study was to assist HDC in identifying and evaluating the energy savings potential available at HSAAP. One of the cost savings measures recommended as a result of the DuPont study involved the recovery of heat from the acetic anhydride manufacturing process at HSAAP's Area A by preheating the combustion air supplied to the ketene furnace burners.[1] A subsequent study, contracted by the Army from the Defense and Space Systems Group of TRW, Inc., recommended that this heat recovery technique be applied to both the producer gas and combustion air streams being fed to the furnace burners.[2]

A review of the TRW proposal with Tennessee Eastman Company (TEC) personnel having experience in this area indicated that any heat exchanger arrangement involving producer gas would probably be unsuccessful because of producer gas decomposition with a resulting carbonaceous buildup on the heat exchanger tubes.[3] As a result of this review, HDC proposed to the Army that the heat exchanger evaluation include only pre-heat of the combustion air stream.[4] The proposal was accepted by the Army and the authorization/funding documentation was prepared on this basis.[5,6,7]

Subtask No. 4 of MM&T Project No. 5804281 was funded on June 10, 1980, to perform the energy conservation work as proposed. Design and installation of a heat exchanger and its related equipment was included in the project scope-of-work along with the heat exchanger evaluation effort. The project objective was to determine the feasibility and economics of using a gas-to-gas heat exchanger to recover a portion of the heat from the hot ketene vapor stream leaving a ketene cracking furnace.

This Final Engineering Report includes pre-operational and standard processing information to provide the background information necessary to understand the procedure used to analyze the project results. Operational data are included in the report in tabular form to permit easy comparison of ketene furnace performance data both with and without the heat exchanger in service, and evaluational results are discussed in the Experimental Section. Results of the evaluation are contained in the Conclusions Section of the report, and the Recommendations Section contains an interpretation of the results with respect to the projected application of the heat recovery process at HSAAP.

EXPERIMENTAL

Subtask No. 4 of MM&T Project No. 5804281 is an energy conservation project involving the partial recovery of heat from the hot ketene/acetic acid vapor produced at Holston Army Ammunition Plant (HSAAP) during the manufacture of crude acetic anhydride. The objective of the project was to determine the feasibility and economics of using a gas-to-gas heat exchanger to recover a portion of the heat from the hot ketene vapor leaving a cracking furnace by using the hot stream to preheat combustion air used in the furnace burners. The scope of work included design, procurement, installation, and evaluation of a heat exchanger and related equipment to assess the potential benefits of the heat recovery process for HSAAP. The results of the evaluation work and the economic analysis of the process are included in this report.

EXPERIMENTAL: PRE-OPERATIONAL INFORMATION

Acetic Anhydride Manufacturing Process Description

Crude acetic anhydride is manufactured at HSAAP by thermally cracking glacial acetic acid in producer gas fired furnaces to form ketene and water. The pyrolytic conversion of acetic acid to ketene is carried out under reduced pressure at a temperature of 700-800°C (973-1073 K). An acidic catalyst and a stabilizer are added to the vaporized acetic acid feed to promote the pyrolysis and inhibit the recombination of ketene and water. The vaporized ketene-acetic acid-water stream is pulled by the vacuum directly from the crucible coil of the furnace through a quick cooling train consisting of one water-cooled condenser and three glycol condensers to rapidly cool the product gases to remove water and acetic acid. The ketene, still in the gaseous state, is then reacted directly with acetic acid in the scrubber system on a mole-per-mole basis to produce an anhydride/acid mixture of approximately 82% anhydride concentration. Figure 1 shows a flow diagram of the crude anhydride manufacturing process.

Heat Recovery Process Description

The heat recovery process evaluated in this project involves the addition of a gas-to-gas heat exchanger to the standard acetic anhydride manufacturing process to preheat furnace combustion air with the hot ketene stream produced in the cracking furnace. The heat exchanger was installed in the ketene line between the crucible coil of Ketene Furnace No. 23 and the water/glycol condensers used by the furnace to remove water and acetic acid (see Figure 2). The heat recovery process simply reroutes ambient temperature air being fed to the furnace burners through the heat exchanger on the shell side in counter-current flow to the flow of hot ketene (tube side). Both the air and ketene streams flow through the heat exchanger in a single pass, but the heated air is divided into two streams as it exits the heat exchanger in order to accomodate the expanded volume and to provide separate service to the two burners.

An ambient air by-pass line permits air flow to be directed to the burners without pre-heating. It was included primarily, however, to permit blending of ambient air with heated air to control both air temperature and the heat transfer rate affecting the temperature of the ketene exiting the heat exchanger - a temperature that has to be maintained at a minimum of 350°C (623 K) to avoid corrosion problems and to maintain furnace yield.

The initial installation used special high-temperature gages (427°C/700 K) to indicate temperatures of the heated air streams leaving the heat exchanger and a standard-range gage to measure ambient air temperature. (Note: Operational problems during the initial start-up required that the high-temperature gages be replaced with thermocouples.) A flowmeter with rate indicator was used to measure ambient air flow rate and to totalize air usage. The available air flow manometers were used to indicate volumetric flow rate of heated combustion air. Producer gas flow rates were measured using orifice meters with the converted signals recorded on a two-pen flow recorder. The remaining process data, i.e., ketene mass flow rate and inlet/outlet heat exchanger temperatures were included in the standard furnace operational data monitor maintained by the operating personnel to control the ketene cracking furnace process.

Equipment Procurement and Installation

The project scope of work provided for the design and purchase of a gas-to-gas heat exchanger to evaluate heat recovery from the acetic anhydride manufacturing process. However, a review of excess inventory at HSAAP indicated that a heat exchanger for high temperature service was available on site that could potentially be used. An analysis of the heat transfer characteristics and pressure drop calculations for the heat exchanger confirmed that it was suitable for use in the ketene cooldown evaluation.[8] Use of the heat exchanger in the project was approved, and piping design was based on the dimensional data of the exchanger. Use of the HSAAP heat exchanger precluded the need for a DIPEC (Defense Industrial Plant Equipment Center) search for a potentially suitable heat exchanger somewhere else in the government inventory system, but the anticipated shortening of the equipment procurement phase of the project was later nullified when the vortex flowmeter (for measuring air flow) and the special high-temperature gages proved to have much longer delivery times than expected.

A local firm, Midwest Technical Incorporated (MTI), was subcontracted by Holston Defense Corporation (HDC) to perform the engineering design and drafting work for the project. HDC Engineering supplied dimensional and structural data for the heat exchanger (see Figure 3) and site location data. MTI's drawing package was approved, and the materials list (stores items) and purchase requisitions (non-stores equipment and materials) were issued to procure instruments and installation materials.

Installation work began when the heat exchanger was mounted above Ketene Furnace No. 23 in Building 7A. Fabrication of the piping also began and continued intermittantly. The fabrication/installation work effort was hindered throughout this time period by the slow delivery of non-stores equipment (instruments) and materials (flexible SS piping). The vortex flow meter

and high-temperature gages were finally received and installed. With their installation and the completion of insulation work on the hot process lines that were reasonably accessible to the operating personnel, installation work on the ketene cooldown heat exchanger was completed.

In addition to the heat exchanger installation, piping connections were installed to permit separate collection of the crude acetic anhydride produced in Ketene Furnace No. 23 and its associated scrubber system. This was done to allow quality and quantity comparisons between the furnace using pre-heated combustion air and the furnaces using ambient temperature air - an important processing assessment required for the heat recovery process evaluation.

Hazards Analysis

A preliminary Hazards Analysis (PHA) for the ketene cooldown heat exchanger and process was performed to identify and evaluate the potential safety problems associated with the project.[9] The primary problem area was considered to be the increased exposure of operators to thermal burn hazards because of the increased hot surface areas involved. The use of insulation to minimize this hazard was recommended in the PHA, and the recommendation was implemented during installation of the process equipment and piping. The safety hazards associated with ketene toxicity and ketene/air flammable mixtures were considered to be essentially unchanged by using the heat exchanger with the standard ketene furnace process. Special safety requirements were not considered necessary and none were recommended.

Ketene Cracking Furnace Process Control

Process control of the ketene furnaces requires constant operator attention. All process control instrumentation is monitored continuously and the data recorded hourly. The recovered weak acid that is condensed in the water/glycol coolers is analyzed hourly, and the acid concentration is used as the primary control parameter for the process. The control standard is an acid concentration of approximately 40 percent, and higher concentrations indicate either inadequate ketene conversion because of low crucible coil temperature or reconversion of ketene to acetic acid because of a slowed cooling rate of the ketene stream.

Fluctuations in producer gas fuel quality and pressure necessitate frequent furnace temperature adjustments to maintain the desired weak acid concentration. The temperature adjustments are made by manually resetting the flow control valves for producer gas, combustion air and draft air to maintain a crucible coil temperature of approximately 1,000 °C (1273 K). The frequency of adjustment and the relatively slow response of the process to control adjustments made direct cause/effect data assessment impossible during the evaluation. For this reason process temperature and flow data had to be averaged to permit comparisons between the standard process (ambient combustion air) and the modified process (pre-heated combustion air). Monthly data averages are presented in tabular form in this report to clearly show the operational and economic potential of the ketene cooldown heat exchanger process for HSAAP. However, caution must be used when interpreting the data since the frequent process adjustments and resulting process fluctuations can easily cause data to vary ± 5 percent.

EXPERIMENTAL: OPERATIONAL EVALUATION

Initial Heat Exchanger Start-Up Problems

When ketene furnace operations were transferred into the 8-furnace operating quadrant where the heat exchanger installation was located, preheat of Ketene Furnace No. 23 began but start-up of the furnace was delayed because of leaks in the vacuum scrubber system that prevented sufficient vacuum from being maintained on the system.

Start-up of the furnace proceeded normally with the introduction of partial feed to the coils, but problems with the heat exchanger system were immediately encountered. An imbalance of air flow caused severe overheating in one of the combustion air lines. The "cherry red" condition of the overheated line was not eliminated by opening the air by-pass valve to blend hot and cold air being fed to the burners. As a result, one of the special high-temperature gages was ruined when it exceeded its maximum scale reading of 427°C (700 K), and the hot line caused the paper backing on the aluminum insulation covering to ignite. The small flame was quickly extinguished, but the conditions and controls for meaningful data collection were obviously absent and the furnace was shut down within 20 minutes after start-up. The furnace was restarted using normal ketene/air flow conditions (without the heat exchanger) to compile baseline data for product quality while specific modifications to the evaluational equipment were being planned and implemented.

The following modifications to the ketene cooldown heat exchanger process were approved for installation prior to re-start of the heat exchanger evaluation (See Figure 4 for identification coding of these modifications):

1. Installation of a blocking valve to allow complete by-pass of the air stream.

2. Installation of a throttling valve in the "high-flow" heated combustion air line.

3. Installation of new high temperature gaskets on the heat exchanger.

4. Rerouting of the inlet air line to isolate it from the heated air lines.

5. Connect inlet air line to a "sole-source" air supply fan.

6. Installation of thermocouples to the temperature recorder for Furnace 24 (not in service) to replace temperature gages damaged during initial startup.

7. Replacement of improper insulation on the ketene line from furnace.

8. Install a blank in the acid return line.

These modifications were designed to permit the ketene furnace to reach steady-state conditions before controlled pre-heating of combustion air was attempted. In addition, it permitted adjustment of the air flow rate in the hot air lines to balance the air flow to the two burners and thus prevent the overheating situation that occurred during the initial start-up. The modifications also added considerable flexibility to the operational design since they allowed shutdown and re-start of the heat exchanger evaluation without having to stop and re-start furnace operations. The modifications proved to be successful when the re-start of the heat exchanger evaluation was accomplished without incident.

Operation of Ketene Furnace No. 23 Without the Heat Exchanger

Ketene Furnace No. 23 was restarted within 4 hours after the heat exchanger evaluation was stopped. Operational "baseline" data was collected to use in comparing standard furnace operating performance with furnace operation when using the heat exchanger to preheat combustion air.

Tables 1 and 2 give the primary operating data for Ketene Furnace No. 23, baseline tests no. 1 and no. 2, respectively. The data is provided in daily averages and summarized on a monthly basis in the form of a 24-hour average.

Restart/Line-Out Operation of the Ketene Furnace and Heat Exchanger

The required modifications to the heat exchanger process were delayed because of delivery problems associated with the special high temperature-resistant insulation material ordered to replace the inadequate insulation used during the initial start-up. After installation work was completed, Ketene Furnace No. 23 was restarted. Ambient temperature combustion air was used until furnace conditions were stabilized with a reduced feed rate of 800 lbs/hr (1.01 E-01 kg/s). Then controlled blending of ambient and heated combustion air was initiated to control the air temperature. A blended air temperature of 159°C (432 K) was obtained by opening the air blocking valve one notch (see adjustment number 2 in Table 3). This temperature was maintained throughout the transition period from partial to full feed rate at standard furnace conditions. Then, after furnace feed and temperature controls were stabilized, additional air blending was tried on a graduated basis until heating of the total combustion air stream was reached.

Table 3 shows the effects of the various air valve adjustments on the temperatures of both combustion air and ketene as these streams exited the heat exchanger. The maximum resulting combustion air temperature of 360°C (633 K) produced a corresponding reduction in ketene temperature to 460°C (733 K) - a temperature well above the minimum 350°C (623 K) temperature level that was considered critical for maintaining furnace yield and preventing excessive corrosion. Since this temperature "balance" was reached at stable furnace operation at full feed rate, the data showed that a wide disparity existed between actual performance data and the theoretical data used to project economic benefits. Subsequent data analysis

showed that only one-third as much combustion air was being fed to the furnace burners, i.e. controlled air usage, as the DuPont report had originally projected.[1]

Controlled blending of ambient air with the air heated via flow through the heat exchanger was very effective in controlling the combustion air temperatures. Adjustment numbers 13-16 in Table 3 show that abrupt adjustments were made to test the technique, and the effects on furnace control were easily handled by normal operator monitor of the furnace conditions.

The primary furnace operating data for the first month (Test no. 1) is shown in Table 4. The temperature and flow data for the ketene/air heat exchanger are provided in Tables 5 and 6, respectively. Again, for comparative purposes, the data is provided in daily averages and summarized on a monthly basis in the form of a 24-hour average. Calculations for heat exchanger operation are included in Appendix A, Section II.

Ketene Furnace/Heat Exchanger Operation

Operation of Ketene Furnace No. 23 with maximum pre-heat of combustion air continued without problems. Normal operational data for the furnace and heat exchanger was collected for comparison with the "baseline" data to determine if furnace rates and product quality were being adversely affected by preheat of the combustion air. However, additional data was needed to relate producer gas quality to furnace operational data and to confirm directly the apparent energy savings afforded by the heat exchanger. The second month's operations were directed toward obtaining this additional process data.

To obtain direct confirmation of the energy savings calculated on the basis of heat transfer from the ketene stream to combustion air, furnace operation using ambient temperature air was conducted during a one week time period and the producer gas usage data was compared to the producer gas usage with combustion air preheat. The 24-hour data averages from Table 7 indicated a reduction in gas usage of approximately 4.5 percent when using preheated combustion air. The gas usage reduction calculated from heat transfer data was 3.85 percent (See Appendix A, page 57) - a reasonably close correlation when considering the potential for error in obtaining the raw data. The direct-source data confirmed what the low air flow data had earlier indicated - that cost savings were significantly lower than the original estimates projected.

A considerable effort was made during the second month's operations to obtain producer gas quality data for correlation with gas usage. An initial attempt to obtain gas quality data resulted in an abnormally low average heating value for four producer gas samples of 141.28 BTU/ft^3 (4.22 E+03 J/m^3).[10] Two additional series of analyses resulted in even lower heating values for producer gas than the first. None of these analyses were considered reliable since the heating values were so much lower than those obtained in earlier producer gas characterization studies conducted at HSAAP.[11,12] Useful producer gas heat value data was finally obtained when a new gas chromatograph that had just been calibrated was operated for a period of more than 24 hours. Figure 5 provides a data plot of the producer gas heat values versus time for the 24-hour period. The average heat content value of 153.12 BTU/ft^3 (4.57 E + 03 J/m^3) was used in calculations for heat exchanger operation to provide a

comparison with calculations using an assumed average heat content value throughout the evaluation period of 156 BTU/ft^3 (4.66 E + 03 J/m^3). The calculations are included in Appendix A, Section V.

The furnace operating data for the second month (Test no. 2) is included in Table 7. Temperature and flow data for the ketene/air heat exchanger operations are provided in Tables 8 and 9, respectively. The tabular format with daily averages and the monthly data summary as a 24-hour average has been retained. Calculations for heat exchanger operation are included in Appendix A, Section III. Calculations for operating conditions when the heat exchanger was not used to preheat combustion air are included in Appendix A, Section VI.

Ketene Furnace No. 23 operated without problems using full combustion air preheat for a third month when data collection for the ketene cooldown project was terminated. Efforts to obtain additional producer gas quality versus usage data were unsuccessful because the gas chromatograph in Building 10A was inoperative throughout the month.

The operating data for Ketene Furnace No. 23 for the third month (Test no. 3) Table 10. The temperature and flow data for the ketene/air heat exchanger during the third month operations are provided in Tables 11 and 12, respectively. The averaged-data format is again used to summarize the data. Calculations for heat exchanger operation are included in Appendix A, Section IV.

Discussion of the Operational Results

The first part of the project objective was to determine the feasibility of using a gas-to-gas heat exchanger to recover a portion of the heat from the hot ketene vapor stream leaving a ketene cracking furnace by preheating combustion air being used in the furnace burners. The operational results will be discussed within the context of this part of the project objective.

1. Production Data - Feasibility of the heat exchanger process was dependent upon whether or not heat recovery could be accomplished without decreasing production rate or causing equipment corrosion problems due to the slower ketene cooling rate associated with flow through the heat exchanger. A comparison of the baseline production data (Table 13) and (Table 14) with production (Table 15), (Table 16), and (Table 17), when the heat exchanger was being used to preheat combustion air, reveals that the 24-hour data averages for acetic anhydride production (100% basis) were higher during the months when the heat exchanger process was being used. While the 24-hour averages for anhydride concentration are lower for the heat exchanger evaluation period than for the standard furnace operating months, they were directly in line with established operating specifications. The operational data, therefore, indicates that furnace rates and product quality were not adversely affected by preheating the combustion air.

2. <u>Corrosion/Fouling of the Heat Exchanger</u> - An inspection of the heat exchanger's tube bundle after the heat exchanger was removed from service indicated that neither plugging nor corrosion of the 1-inch (3-cm) tubes had occurred during the 3-month evaluation period. This information, coupled with the yield/quality data, confirms the technical feasibility of using a heat exchanger to preheat combustion air being fed to the furnace burners.

3. <u>Combustion Air Usage</u> - The flow data for combustion air usage during the heat exchanger evaluation period revealed that the quantity, or mass, of air being fed to the burners, i.e., <u>controlled</u> air flow, was significantly lower than the mass flow rates estimated in the initial project planning - approximately one-third of the projected usage and only slightly better than one-half of the theoretical oxygen requirement for burning HSAAP's producer gas (See Appendix B for theoretical oxygen calculations). The result of this reduced usage of controlled combustion air was lower heat recovery and, therefore, reduced cost savings (see the following section for a discussion of the economic analysis of the process).

   The reduced heat recovery provided one positive aspect, however, since the temperature of the ketene stream leaving the heat exchanger never fell below 460°C (733 K) during furnace operation at full feed rate and maximum preheat of combustion air. The absence of plugging and corrosion problems is directly attributable to this process temperature remaining substantially higher throughout the evaluation period than the critical minimum temperature of 350°C (623 K) at which product yield losses and corrosion occur.

4. <u>Draft Air Usage</u> - The low flow rate of <u>controlled</u> combustion air leads to the conclusion that the remainder of the oxygen used to burn the producer gas fuel comes from the draft air supplied to the furnace to influence flue gas removal and to balance the heat loading within the furnace to assist in furnace temperature control. Previous analyses of furnace flue gas indicated an excess of oxygen rather than an oxygen-starved system in which only partial combustion could occur. Since the controlled combustion air flow was only approximately one-half of the theoretical quantity needed for stoichiometric combustion, draft air must be the source of the additional oxygen.

   Table 18 provides a data summary of the operational effects of draft air usage in Ketene Furnace No. 23. The data shows that more draft air was used during standard furnace operation than when heated combustion air was being used. The data also indicates an inverse relationship between draft air usage and combustion (ambient) air usage. This suggests that some overall air usage balance does exist for steady-state furnace operation, and it appears to confirm that draft air is the source of the additional combustion air used to burn producer gas.

5. <u>Water/Glycol Condensers</u> - Table 19 provides a data summary for the water/glycol cooler operation with Ketene Furnace No. 23. The data shows that the cooling

water and glycol removed less heat when the heat exchanger was being used to pre-heat combustion air than during standard operations - a predictable result. The temperature of the cooling water averaged 12°C lower and the glycol temperature averaged 10°C lower than during standard processing. The cost savings associated with the reduction in cooling water and glycol usage was found to be negligible at current 5-furnace operation because of the minimum refrigeration capacity available to provide cold glycol to the ketene quick cooling trains. A single refrigeration unit provides more than enough glycol for the 5-furnace operation. Since cooling water costs are quite low and there were no savings associated with the reduced glycol requirement, no cost savings from this source were considered in the economic analysis.

6. Material/Energy Balances - Material and energy balances for the ketene/air heat exchanger process are contained in Tables 20 - 23 of this report. The best operating data obtained during the evaluation period was used to prepare the balances. The same data was used to prepare the economic evaluation (see Appendix C).

   Tables 20 and 21 provide the material balance data for the heat exchanger in English units and in the International System of Units (SI), respectively. Stream codes used in the tables are letters that are identified in Figure 8 Tables 22 and 23 provide the energy balance data for the heat exchanger in English and SI units, respectively. The tables, again, are letter coded for reference to Figure 8.

   The information contained in the material/energy balance tables is straightforward, but a comment concerning the radiation/convection heat losses from the shell of the heat exchanger as shown in Tables 22 and 23 should put the heat-loss data in perspective. The rather large heat loss of 156,000 BTU/hr (45.7 kJ/s) was initially entered in the tables on a "difference" or "remaining balance" basis. However, a subsequent review of technical literature with respect to heat losses from bare iron pipe for combined radiant and convection heat losses confirmed the magnitude of heat loss for similar diameter piping.[13] A sensitivity analysis of the economic evaluation in the following section of this report will show that full insulation of the heat exchanger could not have sufficiently increased heat recovery to alter the economic attractiveness of the process (see Economic Analysis of the Ketene Cooldown Process).

Economic Analysis of the Ketene Cooldown Process

The second part of the project objective was to determine the economics of the ketene/air heat exchanger process and to assess the cost savings potential for installation of similar, or modified, heat recovery systems on all the production ketene furnaces at HSAAP. An economic analysis of the heat recovery process has been prepared on the basis of producer gas savings projected from the heat recovery associated with the best operating data obtained during the evaluation period--the data from the first month operations. The cost effectiveness of using similar heat exchanger installations at HSAAP was assessed in terms of Profitability Index (10%, 10 years) and Payback Period for both current (5-furnace) and mobilization

(46-furnace) levels of acetic anhydride production. The economic evaluation of the heat recovery process is included in Appendix C of this report.

The significant data from the first month's operations with respect to the economic evaluation were (1) heat exchanger size (246 ft^2; 23 m^2) and (2) quantity of heat saved (137,133 BTU/hr; 40,188 J/s). An estimate of the current installed cost of a heat exchanger of the same size was then obtained from a current cost estimating textbook.[14] The remaining costs for instruments, installation materials and labor were based on actual costs of like kind incurred for the heat exchanger evaluation project. The cost savings were calculated by applying the current cost of producer gas per million BTU's of heat value to the annualized heat savings. The cost savings used in the Profitability Index and Payback Period calculations were adjusted to account for furnace utilization time and equipment service factors. The results of the economic evaluation indicate that the cost savings associated with this heat recovery process do not justify the expense for installation of similar systems at either the current (5-furnace) or mobilization (46-furnace) level of operation at HSAAP.

Cost calculations attendant with a sensitivity analysis of the economic evaluation have not been included in the report, but consideration was given to the potential impact on the cost data if a much higher heat transfer rate could be obtained - perhaps by using a heat exchanger with a much higher heat transfer coefficient that would correspondingly reduce the size and cost of the heat exchanger.

Figure 6 shows a graphical solution for determining the maximum heat transfer rate possible with a 246 ft^2 (23 m^2) heat exchanger. The value obtained, 212,000 BTU/hr (62,128 J/s), is theoretical and represents a heat transfer rate approximately 55 percent higher than the actual rate experienced in the first month's operations (137,133 BTU/hr; 40,188 J/s). The value is unobtainable, but it serves the point of hypothetically determining <u>optimum</u> cost savings and the resulting impact on the Profitability Index. This maximum heat transfer rate, if obtainable, would provide a PI for the current operational level of 1.007 and a PI for mobilization of 1.544. The Payback Period at mobilization production levels would be 4.2 years. These numbers are obviously unattractive and they are based upon optimum, and unrealistic, data.

Figure 7 shows that significant improvements in heat transfer coefficients are equally unrealistic. The calculated value for the heat transfer coefficient available with the evaluational heat exchanger was 0.94 BTU/hr - ft^2-^oF at a log mean temperature difference of 586 K. Since optimum heat transfer only improves the heat transfer coefficient to approximately 1.5 BTU/hr-$ft^2$$^oF$, it can only be concluded that a heat transfer area in excess of 246 ft^2 (23 m^2) would be required to provide the heat savings needed to approach economic justification. Such savings would, however, be nullified by the increased cost of the larger heat exchanger.

In summary, economic justification for installing heat exchangers on the ketene furnaces at Area A was not supported by either the actual operating data or the optimum data considered in the sensitivity analysis.

CONCLUSIONS

1. A gas-to-gas heat exchanger can safely be used to recover heat from the hot ketene stream leaving a ketene cracking furnace without decreasing the rate or quality of crude acetic anhydride production. Results of the 3-month evaluation indicated that combustion air temperature increased an average of 344°C with a corresponding decrease in temperature of the ketene stream of 291°C. The final temperature of the ketene gas exiting the heat exchanger averaged 467°C (740 K) and never threatened to drop to the critical 350°C (623 K) temperature at which recombination of the ketene/water to acetic acid would detrimentally affect yield. An inspection of the heat exchanger at the end of the evaluation confirmed, as expected, that the high final temperature of the ketene stream also prevented any significant occurrence of fouling inside the heat exchanger tube bundle during the 3-month project life. This indicates that a heat exchanger should be able to operate at near optimum heat transfer conditions throughout the on-stream operational period of a ketene cracking furnace - normally between six and eight months.

2. The quantity of oxygen supplied to the furnace burners by combustion air was determined to be approximately one-half of the theoretical amount required to completely burn the producer gas fuel. The remainder of the oxygen needed for combustion is apparently supplied by the draft air introduced to the furnace to provide temperature control within the furnace and to provide a slight negative pressure to influence flue gas removal from the furnace. The result of this situation is that the mass of combustion air available for preheat in the heat exchanger by the ketene is considerably lower than anticipated in initial projections of potential project benefits.

3. The current production level requires only 5 furnaces at any one time; however, in order to insure production readiness and any production surge, rotation of all 8 furnaces within the quadrant are required. Therefore, in order to implement the waste heat recovery system, all 8 furnaces must be equipped with heat exchangers. The total installation cost would be about $276,400 per quadrant (8 furnaces) while the annual savings would amount to only $27,900/yr. This corresponds to a payback of approximately 10 years.

RECOMMENDATIONS

It is recommended that heat exchangers not be purchased and installed at HSAAP to preheat combustion air being fed to the burners on ketene cracking furnaces at Area A. While the ketene cooldown heat exchanger process proved to be technically feasible, the quantity of combustion air being directly supplied to the burners was insufficient to obtain enough transfer of heat to recover the cost of implementing the heat exchanger process in a reasonable time. In addition, because of service rotation between furnaces, the projected economic benefits from this heat recovery process do not justify the expense of installation at current (5-furnace) levels of operation at HSAAP (See Economic Evaluation in Appendix C).

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Table 1. Operating data for Ketene Furnace No. 23 (baseline test no. 1 - first month)

Day	Acetic Acid Feed Rate		Operating Temperatures, °C			Producer Gas Usage		Weak Acid Conc.
	lbs/hr	kg/s	heating chamber	crucible coil	ketene/acid	ft^3/min	m^3/s	%
1-6	-	-	-	-	-	-	-	-
7	1228	1.55 E-01	1114	999	715	*	*	40.4
8	1226	1.54 E-01	1108	1000	720	*	*	40.2
9	1225	1.54 E-01	1121	1001	719	*	*	40.8
10	1225	1.54 E-01	1129	1008	720	*	*	40.6
11	1226	1.54 E-01	1111	998	719	*	*	40.4
12	1238	1.56 E-01	1121	998	721	*	*	40.4
13	1225	1.54 E-01	1127	1002	720	*	*	40.6
14	1224	1.54 E-01	1132	1005	723	*	*	41.0
15	1225	1.54 E-01	1132	1006	722	*	*	41.0
16	1225	1.54 E-01	1142	1006	722	*	*	41.2
17	1220	1.54 E-01	1122	1003	725	*	*	40.1
18	1223	1.54 E-01	1136	1005	726	*	*	40.4
19	1220	1.54 E-01	1134	1010	724	*	*	40.2
20	1220	1.54 E-01	1115	1000	722	*	*	40.5
21	1220	1.54 E-01	1103	990	722	*	*	39.7
22	1220	1.54 E-01	1126	998	720	*	*	41.0
23	1220	1.54 E-01	1135	1001	722	*	*	40.0
24	1220	1.54 E-01	1108	991	722	*	*	39.7
25	1220	1.54 E-01	1119	995	720	*	*	40.9
26	1220	1.54 E-01	1093	989	721	*	*	41.0
27	1220	1.54 E-01	1134	1000	721	*	*	40.9
28	1220	1.54 E-01	1139	1000	721	*	*	40.6
29	1220	1.54 E-01	1133	1000	722	*	*	40.0
30	1220	1.54 E-01	1146	999	722	*	*	40.3
31	1220	1.54 E-01	1132	1000	723	*	*	40.1
24-hr.avg.	1223	1.54 E-01	1124	1000	721	-	-	40.5

* Producer gas flow indicators were not functioning properly so reliable data was unobtainable.

Table 2. Operating data for Ketene Furnace No. 23 (baseline test no. 2 - second month)

Day	Acetic Acid Feed Rate		Operating Temperatures, °C			Producer Gas Usage		Weak Acid Conc.
	lbs/hr	kg/s	heating chamber	crucible coil	ketene/ acid	ft^3/min	m^3/s	%
1	1220	1.54 E-01	1133	1003	723	392	1.85 E-01	40.4
2	1220	1.54 E-01	1144	1006	724	391	1.85 E-01	40.2
3	1220	1.54 E-01	1153	1011	724	388	1.83 E-01	40.8
4	1220	1.54 E-01	1158	1020	723	385	1.82 E-01	41.1
5	1220	1.54 E-01	1180	1034	727	388	1.83 E-01	40.9
6	1220	1.54 E-01	1137	1020	723	380	1.79 E-01	40.7
7	1220	1.54 E-01	1128	1007	724	381	1.80 E-01	39.7
8	1220	1.54 E-01	1128	1008	723	372	1.76 E-01	39.4
9	1220	1.54 E-01	1117	1006	720	373	1.76 E-01	40.3
10	1225	1.54 E-01	1140	1008	720	378	1.78 E-01	40.2
11	1187	1.50 E-01	1153	1018	722	374	1.77 E-01	39.5
12	1220	1.54 E-01	1150	1013	722	371	1.75 E-01	39.7
13	1220	1.54 E-01	1155	1015	721	372	1.76 E-01	40.1
14	1220	1.54 E-01	1149	1018	723	362	1.71 E-01	40.3
15	1220	1.54 E-01	1120	1005	723	368	1.74 E-01	40.5
16	1220	1.54 E-01	1116	1001	718	377	1.78 E-01	40.1
17	1220	1.54 E-01	1124	1003	717	387	1.83 E-01	40.0
18	1220	1.54 E-01	1120	1006	717	389	1.84 E-01	40.0
19	1220	1.54 E-01	1134	1009	717	376	1.77 E-01	40.3
20	1220	1.54 E-01	1133	1011	717	342	1.61 E-01	40.0
21	1220	1.54 E-01	1128	1010	717	360	1.70 E-01	39.8
22	1220	1.54 E-01	1122	1010	716	364	1.72 E-01	40.6
23	1220	1.54 E-01	1123	1010	719	356	1.68 E-01	40.5
24	1220	1.54 E-01	1125	1009	719	362	1.71 E-01	39.7
25	1220	1.54 E-01	1123	1012	718	356	1.68 E-01	39.8
26	1220	1.54 E-01	1108	1002	717	360	1.70 E-01	40.6
27	1220	1.54 E-01	1085	997	720	348	1.64 E-01	37.7
28-30*	-	-	-	-	-	-	-	-
24-hr.avg.	1219	1.54 E-01	1133	1010	721	372	1.76 E-01	40.1

* Baseline data collection ended on the 27th day of the month, with the shutdown of Ketene Furnace No. 23.

Table 3. Effects of air valve adjustments on temperatures of the combustion air and ketene streams leaving the heat exchanger

Adjustment Number	Air Blend Valve Position	Air Blend Valve % Open	Air Block Valve Position	Air Block Valve % Open	Air Temperature °C	Ketene Temperature °C
1	FO	100	FC	0	24	435
2	FO	100	5	36	159	461
3	FO	100	6	50	185	500
4	FO	100	7	66	202	498
5	FO	100	8	83	216	497
6	FO	100	FO	100	212	492
7	5	74	FO	100	212	496
8	4	50	FO	100	220	496
9	3	29	FO	100	237	490
10	2	13	FO	100	265	480
11	1	3	FO	100	329	469
12	FC	0	FO	100	360	460
13	FC	0	FO	100	362	470
14	FO	100	FO	100	218	499
15	FO	100	FC	0	30	540
16	FC	0	FO	100	357	464

Note: FO - Full Open
FC - Full Close

Table 4. Operating data for Ketene Furnace No. 23 - test no. 1

Day	Acetic Acid Feed Rate		Operating Temperatures, °C			Producer Gas Usage		Weak Acid Conc.
	lbs/hr	kg/s	heating chamber	crucible coil	ketene/ acid	ft^3/min	m^3s	%
1-13	-	-	-	-	-	-	-	-
14*	1225	1.54 E-01	1174	1016	746	-	-	40.2
15*	1232	1.55 E-01	1167	1004	752	-	-	40.1
16*	1233	1.55 E-01	1174	1004	752	-	-	40.8
17*	1232	1.55 E-01	1164	1001	754	379	1.79 E-01	40.9
18*	1231	1.55 E-01	1156	1001	759	362	1.71 E-01	40.4
19*	1234	1.55 E-01	1157	999	758	364	1.72 E-01	40.8
20	1235	1.56 E-01	1154	1000	759	362	1.71 E-01	41.0
21	1237	1.56 E-01	1159	1001	755	356	1.68 E-01	40.5
22	1236	1.56 E-01	1140	994	757	355	1.68 E-01	40.3
23	1239	1.56 E-01	1149	1000	763	361	1.70 E-01	39.7
24	1240	1.56 E-01	1157	1001	762	350	1.65 E-01	39.8
25	1240	1.56 E-01	1172	1004	763	344	1.62 E-01	40.3
26	1240	1.56 E-01	1149	997	764	352	1.66 E-01	40.2
27	1240	1.56 E-01	1164	999	761	347	1.64 E-01	40.3
28	1240	1.56 E-01	1160	999	760	351	1.66 E-01	40.0
29	1240	1.56 E-01	1151	999	760	361	1.70 E-01	40.2
30	1240	1.56 E-01	1133	993	759	359	1.69 E-01	40.3
31	1240	1.56 E-01	1150	999	760	356	1.68 E-01	40.4
24-hr.avg.	1239	1.56 E-01	1153	999	760	355	1.68 E-01	40.3

* Data collected during the 14th - 19th day of the month, time period was not used in determining the 24 hour data average since steady-state operation of the heat exchanger (with total combustion air flow being heated) was not reached until the 19th day.

Table 5. Ketene/air heat exchanger temperature data - test no. 1

Day	Ketene/Acid Temp., °C enter exchanger	Ketene/Acid Temp., °C exit exchanger	Ambient Air Temp., °C	Air Temperatures, °C Burner #1	Air Temperatures, °C Burner #2
1-14	-	-	-	-	-
15	752	495	9	202	370
16	752	495	8	206	370
17	754	494	6	210	368
18	759	490	8	246	364
19	758	464	10	337	352
20	759	464	14	363	357
21	755	464	14	364	356
22	757	470	16	364	359
23	763	467	19	365	359
24	762	465	9	362	355
25	763	468	10	361	354
26	764	469	8	360	354
27	761	465	11	359	353
28	760	466	9	360	354
29	760	473	9	361	357
30	759	471	18	362	356
31	760	466	20	363	355
24-hr.avg.*	760	467	12	362	356

* The 24-hour data average reflects the 20th - 31st day operating data. Total combustion air flow was being directed through the heat exchanger during this operating period.

Table 6. Ketene/air heat exchanger flow data - test no. 1

Day	Ketene/Acetic Acid Flow Rate,		Ambient Air Flow Rate		Hot Air Flow Rate		Air Usage Ratio (hot/cold)
	lbs/hr	kg/s	ft^3/min	m^3/s	ft^3/min	m^3/s	
1-14	0	0	0	0	0	0	0
15	1232	1.55 E-01	240	1.13 E-01	290	1.37 E-01	1.2083
16	1233	1.55 E-01	225	1.06 E-01	268	1.26 E-01	1.1911
17	1232	1.55 E-01	214	1.01 E-01	264	1.25 E-01	1.2336
18	1231	1.55 E-01	204	9.63 E-02	256	1.21 E-01	1.2549
19	1234	1.55 E-01	208	9.82 E-02	276	1.30 E-01	1.3269
20*	1235	1.56 E-01	201	9.49 E-02	274	1.29 E-01	1.3632
21*	1237	1.56 E-01	200	9.44 E-02	272	1.28 E-01	1.3600
22*	1236	1.56 E-01	193	9.11 E-02	252	1.19 E-01	1.3057
23*	1239	1.56 E-01	202	9.53 E-02	256	1.21 E-01	1.2673
24*	1240	1.56 E-01	199	9.39 E-02	256	1.21 E-01	1.2864
25*	1240	1.56 E-01	190	8.97 E-02	246	1.16 E-01	1.2947
26*	1240	1.56 E-01	188	8.87 E-02	244	1.15 E-01	1.2979
27*	1240	1.56 E-01	191	9.01 E-02	252	1.19 E-01	1.3194
28*	1240	1.56 E-01	190	8.97 E-02	252	1.19 E-01	1.3263
29*	1240	1.56 E-01	176	8.31 E-02	238	1.12 E-01	1.3523
30*	1240	1.56 E-01	185	8.73 E-02	242	1.14 E-01	1.30[illegible]
31*	1240	1.56 E-01	200	9.44 E-02	258	1.22 E-01	1.2900
24-hr. avg.*	1239	1.56 E-01	193	9.11 E-02	254	1.20 E-01	1.3161

* The 24-hour data average reflects the 20th - 31st day operating data. Total combustion air flow was being directed through the heat exchanger during this operating period.

Table 7. Operating data for Ketene Furnace No. 23 - test no. 2

Day	Acetic Acid Feed Rate lbs/hr	Acetic Acid Feed Rate kg/s	Operating Temperatures, °C heating chamber	Operating Temperatures, °C crucible coil	Operating Temperatures, °C ketene/acid	Producer Gas Usage ft^3/min	Producer Gas Usage $m^3 s$	Weak Acid Conc. %
1	1240	1.56 E-01	1163	999	760	351	1.66 E-01	41.0
2	1240	1.56 E-01	1141	999	762	353	1.67 E-01	40.4
3	1240	1.56 E-01	1149	999	756	356	1.68 E-01	40.4
4	1240	1.56 E-01	1170	1003	758	364	1.72 E-01	39.8
5	1240	1.56 E-01	1164	999	758	356	1.68 E-01	42.0
5*	1240	1.56 E-01	1195	1006	759	364	1.72 E-01	40.7
6*	1240	1.56 E-01	1200	1004	759	362	1.71 E-01	39.9
7*	1240	1.56 E-01	1174	1001	758	357	1.68 E-01	40.3
8*	1240	1.56 E-01	1169	998	761	378	1.78 E-01	40.4
9*	1240	1.56 E-01	1158	997	758	379	1.79 E-01	40.6
10*	1240	1.56 E-01	1162	1000	758	396	1.87 E-01	40.5
11*	1240	1.56 E-01	1176	1006	757	405	1.91 E-01	40.2
12*	1240	1.56 E-01	1147	997	758	424	2.00 E-01	41.0
12	1240	1.56 E-01	1156	999	758	385	1.82 E-01	40.2
13	1240	1.56 E-01	1161	1003	761	399	1.88 E-01	40.3
14	1240	1.56 E-01	1163	1000	761	387	1.83 E-01	40.2
15	1240	1.56 E-01	1156	999	751	371	1.75 E-01	40.4
16	1240	1.56 E-01	1170	998	755	373	1.76 E-01	40.4
17	1240	1.56 E-01	1194	1008	757	345	1.63 E-01	40.1
18	1240	1.56 E-01	1202	1007	752	354	1.67 E-01	40.6
19	1240	1.56 E-01	1226	1009	752	351	1.66 E-01	40.9
20	1248	1.57 E-01	1209	1006	753	351	1.66 E-01	40.6
21	1240	1.56 E-01	1211	1008	754	349	1.65 E-01	40.2
22	1240	1.56 E-01	1206	1005	754	354	1.67 E-01	40.3
23	1240	1.56 E-01	1200	1005	753	360	1.70 E-01	40.0
24	1240	1.56 E-01	1200	1005	753	361	1.70 E-01	40.6
25	1240	1.56 E-01	1198	1007	757	354	1.67 E-01	39.8
26	1240	1.56 E-01	1211	1006	757	358	1.69 E-01	39.9
27	1240	1.56 E-01	1197	997	756	368	1.74 E-01	40.6
28	1240	1.56 E-01	1215	1004	757	372	1.76 E-01	40.0
24-hr.avg.	1240	1.56 E-01	1185	1003	756	362	1.71 E-01	40.4
24-hr.avg.*	1240	1.56 E-01	1173	1001	759	379	1.79 E-01	40.5

*Data reflects operation with combustion air by-passing heat exchanger.

Table 8. Ketene/air heat exchanger temperature data - test no. 2

Day[a]	Ketene/Acid Temp., °C enter exchanger	Ketene/Acid Temp., °C exit exchanger	Ambient Air Temp., °C	Air Temperatures, °C Burner #1	Air Temperatures, °C Burner #2[b]
1	760	472	12	362	357
2	762	469	12	362	354
3	756	466	19	362	356
4	758	466	14	361	357
5	758	469	15	359	358
5	759	539	15	32	404
6	759	540	11	29	403
7	758	540	7	30	403
8	761	539	12	30	401
9	758	538	14	31	405
10	758	539	9	32	407
11	757	539	12	34	406
12	758	540	12	30	404
12	758	462	12	357	355
13	761	464	9	357	356
14	761	467	13	357	358
15	751	463	17	358	357
16	755	463	18	359	358
17	757	465	19	360	359
18	752	461	17	357	357
19	752	462	15	356	356
20	753	464	17	358	358
21	754	465	17	358	359
22	754	466	12	359	359
23	753	465	17	359	356
24	753	466	22	360	360
25	757	467	14	360	359
26	757	467	11	359	359
27	756	468	12	360	360
28	757	468	16	361	360
24-hr.avg.	756	466	15	359	358
24-hr.avg.	759	539	12	31	404

[a] Reflects operation with combustion air by-passing heat exchanger for days 5 - 12.

[b] The thermocouple for measuring temperature in the air line to Burner #2 was located in the section of line between the heat exchanger and the tie-in with ambient air for days 5 - 12. As a result, this thermocouple was measuring the temperature of stagnant air in the line near the heat exchanger during this operating period where combustion air was by-passing the heat exchanger. The air temperature for both burners was essentially the same as shown for Burner #1 where the temperature was measured in the piping downstream from the ambient air tie-in. Air temperatures for both burners were accurately reflected by the thermocouples during all variations of hot/cold air blending.

Table 9. Ketene/air heat exchanger flow data - test no. [illegible]

Day	Ketene/Acetic Acid Flow Rate, lbs/hr	Ketene/Acetic Acid Flow Rate, kg/s	Ambient Air Flow Rate ft^3/min	Ambient Air Flow Rate m^3/s	Hot Air Flow Rate ft^3/min	Hot Air Flow Rate m^3/s	Air Usage Ratio (hot/cold)
1	1240	1.56 E-01	177	8.35 E-02	236	1.11 E-01	1.3333
2	1240	1.56 E-01	191	9.01 E-02	246	1.16 E-01	1.2880
3	1240	1.56 E-01	201	9.49 E-02	256	1.21 E-01	1.2736
4	1240	1.56 E-01	193	9.11 E-02	248	1.17 E-01	1.2850
5	1240	1.56 E-01	177	8.35 E-02	226	1.07 E-01	1.2768
5*	1240	1.56 E-01	207	9.77 E-02	222	1.05 E-01	1.0725
6*	1240	1.56 E-01	205	9.67 E-02	218	1.03 E-01	1.0634
7*	1240	1.56 E-01	185	8.73 E-02	206	9.72 E-02	1.1135
8*	1240	1.56 E-01	170	8.02 E-02	200	9.44 E-02	1.1765
9*	1240	1.56 E-01	199	9.39 E-02	208	9.82 E-02	1.0452
10*	1240	1.56 E-01	193	9.11 E-02	208	9.82 E-02	1.0777
11*	1240	1.56 E-01	191	9.01 E-02	208	9.82 E-02	1.0890
12*	1240	1.56 E-01	177	8.35 E-02	200	9.44 E-02	1.1299
12	1240	1.56 E-01	197	9.30 E-02	262	1.24 E-01	1.3299
13	1240	1.56 E-01	193	9.11 E-02	248	1.17 E-01	1.2850
14	1240	1.56 E-01	184	8.68 E-02	240	1.13 E-01	1.3043
15	1240	1.56 E-01	201	9.49 E-02	254	1.20 E-01	1.2637
16	1240	1.56 E-01	203	9.58 E-02	258	1.22 E-01	1.2709
17	1240	1.56 E-01	203	9.58 E-02	260	1.23 E-01	1.2808
18	1240	1.56 E-01	204	9.63 E-02	260	1.23 E-01	1.2745
19	1240	1.56 E-01	202	9.53 E-02	258	1.22 E-01	1.2772
20	1248	1.57 E-01	196	9.25 E-02	250	1.18 E-01	1.2755
21	1240	1.56 E-01	200	9.44 E-02	250	1.18 E-01	1.2500
22	1240	1.56 E-01	194	9.16 E-02	250	1.18 E-01	1.2887
23	1240	1.56 E-01	199	9.39 E-02	250	1.18 E-01	1.2563
24	1240	1.56 E-01	196	9.25 E-02	250	1.18 E-01	1.2755
25	1240	1.56 E-01	188	8.87 E-02	246	1.16 E-01	1.3085
26	1240	1.56 E-01	190	8.97 E-02	250	1.18 E-01	1.3158
27	1240	1.56 E-01	185	8.73 E-02	244	1.15 E-01	1.3189
28	1240	1.56 E-01	190	8.97 E-02	250	1.18 E-01	1.3158
24-hr.avg.	1240	1.56 E-01	194	9.16 E-02	250	1.18 E-01	1.2887
24-hr.avg.*	1240	1.56 E-01	192	9.06 E-02	209	9.86 E-02	1.0885

*Reflects operation with combustion air by-passing heat exchanger.

Table 10. Operating data for Ketene Furnace No. 23 - test no. 3

Day	Acetic Acid Feed Rate		Operating Temperatures, °C			Producer Gas Usage		Weak Acid Conc.
	lbs/hr	kg/s	heating chamber	crucible coil	ketene/acid	ft^3/min	m^3s	%
1	1240	1.56 E-01	1204	1001	756	361	1.70 E-01	40.5
2	1240	1.56 E-01	1189	995	760	363	1.71 E-01	40.1
3	1240	1.56 E-01	1194	999	760	364	1.72 E-01	40.9
4	1240	1.56 E-01	1181	996	758	370	1.75 E-01	40.1
5	1240	1.56 E-01	1204	1000	760	361	1.70 E-01	40.3
6	1240	1.56 E-01	1217	1003	762	362	1.71 E-01	39.8
7	1240	1.56 E-01	1243	1017	760	349	1.65 E-01	39.8
8	1240	1.56 E-01	1241	1017	760	356	1.68 E-01	39.7
9	1240	1.56 E-01	1227	1011	758	358	1.69 E-01	40.0
10	1240	1.56 E-01	1226	1008	756	360	1.70 E-01	39.9
11	1230	1.55 E-01	1213	1004	755	361	1.70 E-01	40.4
12	1230	1.55 E-01	1206	1002	757	364	1.72 E-01	40.2
13	1240	1.56 E-01	1214	1001	759	361	1.70 E-01	40.1
14	1240	1.56 E-01	1207	1000	758	353	1.67 E-01	40.4
15	1240	1.56 E-01	1203	994	755	364	1.72 E-01	40.6
16	1240	1.56 E-01	1173	992	758	373	1.76 E-01	40.2
17	1240	1.56 E-01	1177	987	754	377	1.78 E-01	40.4
18	1240	1.56 E-01	1222	1004	756	355	1.68 E-01	40.0
19	1240	1.56 E-01	1186	994	754	360	1.70 E-01	40.7
20	1240	1.56 E-01	1197	995	754	388	1.83 E-01	40.9
21	1240	1.56 E-01	1229	1002	757	398	1.88 E-01	40.3
22	1240	1.56 E-01	1222	1004	758	366	1.73 E-01	40.2
23	1240	1.56 E-01	1201	999	757	381	1.80 E-01	40.3
24	1240	1.56 E-01	1215	1001	757	379	1.79 E-01	40.8
25	1240	1.56 E-01	1227	1002	758	390	1.84 E-01	40.9
26	1240	1.56 E-01	1241	1016	760	359	1.69 E-01	40.6
27	1240	1.56 E-01	1214	1005	760	372	1.76 E-01	40.3
28	1240	1.56 E-01	1223	1003	753	389	1.84 E-01	41.2
29-31*	-	-	-	-	-	-	-	-
24-hr.avg.	1239	1.56 E-01	1210	1002	758	370	1.75 E-01	40.3

* Data collection for the heat exchanger project was completed as of the 28th day of the month.

Table 11. Ketene/air heat exchanger temperature data - test no. 3

Day	Ketene/Acid Temp., °C enter exchanger	Ketene/Acid Temp., °C exit exchanger	Ambient Air Temp., °C	Air Temperatures, °C Burner #1	Air Temperatures, °C Burner #2
1	756	465	16	360	360
2	760	470	17	361	361
3	760	468	19	360	361
4	758	468	23	362	361
5	760	466	18	361	360
6	762	469	17	361	361
7	760	466	12	360	360
8	760	467	11	359	359
9	758	467	16	360	360
10	756	469	20	361	361
11	755	469	20	361	361
12	757	469	24	362	362
13	759	471	21	363	363
14	758	473	15	361	363
15	755	475	18	360	362
16	758	472	19	362	362
17	754	466	24	361	360
18	756	465	24	360	360
19	754	466	23	360	360
20	754	466	25	361	361
21	757	467	22	360	360
22	758	464	17	358	358
23	757	465	16	359	359
24	757	464	18	358	358
25	758	464	21	359	359
26	760	466	13	358	357
27	760	475	10	360	360
28	753	475	12	359	360
29-31*	-	-	-	-	-
24-hr.avg.	758	468	18	360	360

* Heat exchanger operational data was not recorded after the 28th day of the month.

Table 12. Ketene/air heat exchanger flow data - test no. 3

Day	Ketene/Acetic Acid Flow Rate, lbs/hr	Ketene/Acetic Acid Flow Rate, kg/s	Ambient Air Flow Rate ft^3/min	Ambient Air Flow Rate m^3/s	Hot Air Flow Rate ft^3/min	Hot Air Flow Rate m^3/s	Air Usage Ratio (hot/cold)
1	1240	1.56 E-01	195	9.20 E-02	250	1.18 E-01	1.2821
2	1240	1.56 E-01	198	9.34 E-02	250	1.18 E-01	1.2626
3	1240	1.56 E-01	193	9.11 E-02	250	1.18 E-01	1.2953
4	1240	1.56 E-01	208	9.82 E-02	254	1.20 E-01	1.2212
5	1240	1.56 E-01	198	9.34 E-02	260	1.23 E-01	1.3131
6	1240	1.56 E-01	203	9.58 E-02	260	1.23 E-01	1.2808
7	1240	1.56 E-01	201	9.49 E-02	258	1.22 E-01	1.2836
8	1240	1.56 E-01	196	9.25 E-02	250	1.18 E-01	1.2755
9	1240	1.56 E-01	196	9.25 E-02	250	1.18 E-01	1.2755
10	1240	1.56 E-01	198	9.34 E-02	250	1.18 E-01	1.2626
11	1230	1.55 E-01	198	9.34 E-02	250	1.18 E-01	1.2626
12	1230	1.55 E-01	195	9.20 E-02	250	1.18 E-01	1.2821
13	1240	1.56 E-01	197	9.30 E-02	248	1.17 E-01	1.2589
14	1240	1.56 E-01	177	8.35 E-02	234	1.10 E-01	1.3220
15	1240	1.56 E-01	173	8.16 E-02	220	1.04 E-01	1.2717
16	1240	1.56 E-01	188	8.87 E-02	238	1.12 E-01	1.2660
17	1240	1.56 E-01	202	9.53 E-02	256	1.21 E-01	1.2673
18	1240	1.56 E-01	198	9.34 E-02	250	1.18 E-01	1.2626
19	1240	1.56 E-01	201	9.49 E-02	246	1.16 E-01	1.2239
20	1240	1.56 E-01	203	9.58 E-02	250	1.18 E-01	1.2315
21	1240	1.56 E-01	204	9.63 E-02	250	1.18 E-01	1.2255
22	1240	1.56 E-01	203	9.58 E-02	260	1.23 E-01	1.2808
23	1240	1.56 E-01	202	9.53 E-02	260	1.23 E-01	1.2871
24	1240	1.56 E-01	203	9.58 E-02	260	1.23 E-01	1.2808
25	1240	1.56 E-01	203	9.58 E-02	260	1.23 E-01	1.2808
26	1240	1.56 E-01	204	9.63 E-02	260	1.23 E-01	1.2745
27	1240	1.56 E-01	168	7.93 E-02	228	1.08 E-01	1.3571
28	1240	1.56 E-01	166	7.83 E-02	220	1.04 E-01	1.3253
29-31*	-	-	-	-	-	-	-
24-hr.avg.	1239	1.56 E-01	195	9.20 E-02	249	1.18 E-01	1.2755

* Heat exchanger operational data was not recorded after the 28th day of the month.

Table 13. Crude acetic anhydride production data for Ketene Furnace No. 23 (baseline test no. 1 - first month)

Day	Production Time, hrs.	Daily Anhydride Production (100% basis) lbs	Daily Anhydride Production (100% basis) kg	Average Daily Anhydride Conc. %
1-6	0	0	0	0
7	12	16,746	7,596	83.7
8	24	30,416	13,797	83.2
9	24	30,069	13,639	83.6
10	24	30,141	13,672	83.8
11	24	30,932	14,031	83.9
12	24	31,153	14,131	84.5
13	24	31,610	14,338	83.7
14	24	31,346	14,219	83.0
15	24	31,157	14,133	82.5
16	24	31,079	14,097	83.6
17	24	32,518	14,750	84.1
18	24	31,989	14,510	83.4
19	24	32,021	14,525	84.1
20	24	31,614	14,340	84.4
21	24	32,479	14,732	84.0
22	24	32,021	14,525	84.1
23	24	31,686	14,373	83.9
24	24	31,907	14,473	83.8
25	24	31,352	14,221	83.7
26	24	31,005	14,064	84.1
27	24	31,389	14,238	83.8
28	24	31,314	14,204	83.6
29	24	31,314	14,204	83.6
30	24	31,154	14,131	83.8
31	24	31,042	14,081	83.5
Totals	588	769,454	349,024	-
24-hr. avg.	-	31,406	14,246	83.7

Table 14. Crude acetic anhydride production data for Ketene Furnace No. 23 (baseline test no. 2 - second month)

Day	Production Time, hrs.	Daily Anhydride Production (100% basis) lbs	kg	Average Daily Anhydride Conc. %
1	24	31,539	14,306	84.2
2	24	31,577	14,323	84.3
3	24	31,427	14,255	83.9
4	24	31,983	14,507	84.0
5	24	32,450	14,719	84.6
6	24	31,907	14,473	83.8
7	24	32,258	14,632	84.1
8	24	32,296	14,649	84.2
9	24	32,098	14,560	84.3
10	24	32,595	14,785	84.3
11	24	31,799	14,424	84.2
12	24	32,174	14,594	84.5
13	24	31,950	14,493	84.6
14	24	32,136	14,577	84.4
15	24	31,799	14,424	84.2
16	24	31,762	14,407	84.1
17	24	32,060	14,542	84.2
18	24	31,913	14,476	84.5
19	24	32,739	14,850	83.4
20	24	31,881	14,461	81.8
21	24	32,386	14,690	82.5
22	24	32,193	14,603	82.6
23	24	31,899	14,469	82.5
24	24	32,232	14,620	82.7
25	24	32,310	14,656	82.9
26	24	32,681	14,824	82.6
27	2.5	3,448	1,564	81.8
28-30	0	0	0	0
Totals	626.5	837,492	379,883	-
24-hr.avg.	-	32,083	14,553	83.7

Table 15. Crude acetic anhydride production data for Ketene Furnace No. 23 - test no. 1

Day	Production Time, hrs	Daily Anhydride Production (100% basis) lbs	kg	Average Daily Anhydride Conc. %
1-13	0	0	0	0
14	16	14,433	6,547	84.2
15	24	32,936	14,940	82.6
16	24	32,776	14,867	82.2
17	24	31,803	14,426	81.6
18	24	32,229	14,619	82.1
19	24	32,694	14,830	82.4
20	24	32,816	14,885	82.3
21	24	31,959	14,497	82.0
22	24	32,464	14,726	82.7
23	24	32,736	14,849	82.1
24	24	33,475	15,184	82.1
25	24	32,816	14,885	82.3
26	24	34,296	15,557	82.3
27	24	33,019	14,977	81.6
28	24	34,046	15,443	81.7
29	24	34,042	15,441	82.3
30	24	34,486	15,643	82.2
31	24	34,296	15,557	82.3
Totals	424	577,322	261,873	-
24-hr.avg.	-	32,679	14,823	82.2

Table 16. Crude acetic anhydride production data for Ketene Furnace No. 23 - test no. 2

Day	Production Time, hrs	Daily Anhydride Production (100% basis) lbs	kg	Average Daily Anhydride Conc. %
1	24	34,338	15,576	82.4
2	24	34,213	15,519	82.1
3	24	34,360	15,586	81.9
4	24	34,213	15,519	82.1
5	24	32,115	14,567	82.4
6	24	33,515	15,202	82.2
7	24	33,746	15,307	82.2
8	24	32,697	14,831	82.0
9	24	31,491	14,284	82.1
10	24	32,657	14,813	81.9
11	24	32,847	14,899	81.8
12	24	32,657	14,813	81.9
13	24	32,927	14,936	82.0
14	24	33,007	14,972	82.2
15	24	33,261	15,087	82.2
16	24	33,047	14,990	82.3
17	24	33,383	15,143	82.5
18	24	32,562	14,770	82.3
19	24	33,541	15,214	81.7
20	24	33,623	15,251	81.9
21	24	33,794	15,329	81.7
22	24	34,380	15,595	82.5
23	24	33,180	15,050	82.0
24	24	32,856	14,903	82.4
25	24	33,088	15,009	82.4
26	24	33,597	15,240	82.4
27	24	34,166	15,498	82.6
28	24	33,342	15,124	82.4
Totals	672	932,603	423,027	-
24-hr.avg.	-	33,307	15,108	81.9

Table 17. Crude acetic anhydride production data for Ketene Furnace No. [illegible]3 - test no. 3

Day	Production Time, hrs.	Daily Anhydride Production (100% basis) lbs	kg	Average Daily Anhydride Conc. %
1	24	32,856	14,903	82.4
2	24	33,719	15,295	82.7
3	24	33,383	15,143	82.5
4	24	33,597	15,240	82.4
5	24	33,638	15,258	82.5
6	24	33,208	15,063	82.7
7	24	33,475	15,184	82.1
8	24	33,794	15,329	81.7
9	24	33,911	15,382	82.6
10	24	33,221	15,069	82.1
11	24	33,541	15,214	81.7
12	24	33,047	14,990	82.3
13	24	34,130	15,481	81.9
14	24	32,887	14,918	81.9
15	24	33,047	14,990	82.3
16	24	33,556	15,221	82.3
17	24	34,951	15,854	82.1
18	24	30,410	13,794	81.8
19	24	32,537	14,759	81.6
20	24	33,418	15,158	81.4
21	24	33,515	15,202	82.2
22	24	32,847	14.899	81.8
23	24	33,352	15,128	81.8
24	24	33,302	15,106	82.3
25	24	32,967	14,954	82.1
26	24	33,221	15,069	82.1
27	24	33,434	15,166	82.0
28	24	33,088	15,009	82.4
29	24	33,638	15,258	82.5
30	24	33,788	15,326	82.3
31	24	33,664	15,270	82.0
Totals	744	1,033,142	468,632	-
24-hr.avg.	-	33,327	15,117	82.2

Table 18. Data summary of the operational effects of draft air usage in Ketene Furnace No. 23

Test[a,b]	Air draft in heating chamber		Ambient air usage		Producer gas usage[c]		Flue gas exit temp.
	In. water	Pa	ft^3/min	m^3/s	ft^3/min	m^3/s	°C
Baseline no. 1	1.69	4.21 E+02	158	7.46 E-02			266
Baseline no. 2	1.79	4.45 E+02	163	7.69 E-02	372	1.76 E-01	279
Test no. 1	1.23	3.06 E+02	193	9.11 E-02	355	1.68 E-01	306
Test no. 2	1.31	3.26 E+02	194	9.16 E-02	362	1.71 E-01	303
Test no. 2	1.32	3.28 E+02	192	9.06 E-02	379	1.79 E-01	304
Test no. 3	1.41	3.51 E+02	195	9.20 E-02	370	1.75 E-01	300

a Averaged data for draft air usage during test no. 2 (1.31 in. water) when the furnace combustion air was being heated in the heat exchanger (approximately 21 days).

b Averaged data for draft air usage during test no. 2 (1.32 in. water) when the furnace combustion air was not being heated in the heat exchanger (approximately 7 days).

c Producer gas flow indicators were not functioning properly so reliable data was unobtainable for baseline nos. 1 and 2.

Table 19. Data summary of the water/glycol cooler operation with Ketene Furnace No. 23

Test[a,b]	Temp of Ketene into cooler[c] °C	Conc of weak acid condensate %		Ketene temp during cooling °C		
		Water cooler	Glycol coolers	Water	Glycol	Gycol
Baseline no. 1	721	40.5	50.0	63	34	2
Baseline no. 2	721	40.1	49.5	60	33	2
Test no. 1	467	40.3	58.3	48	21	0
Test no. 2	466	40.4	59.2	50	24	1
Test no. 2	539	40.5	58.7	50	28	2
Test no. 3	468	40.3	57.3	50	22	2

[a] Averaged data for cooler performance during test no. 2 (466°C) when the furnace combustion air was being heated in the heat exchanger (approximately 21 days).

[b] Averaged data for cooler performance during test no. 2 (539°C) when the furnace combustion air was not being heated in the heat exchanger (approximately 7 days).

[c] The last four numbers in this column represent temperatures of ketene gas as it exits from the heat exchanger rather than from the crucible coil of the furnace.

Table 20. Material balance for the ketene cooldown heat exchanger (English units)

Basis: 1 hour of operation

Stream Code*	Stream Description	Ketene, lbs	Water, lbs	Acetic Acid, lbs	Air lbs
A	Ketene/Acetic Acid from Ketene Furnace No. 23	699	300	240	-
B	Ketene/Acetic Acid to Quick Cooling Train	699	300	240	-
C	Ambient Air From Blower	-	-	-	897
D	Hot Combustion Air to Burner No. 1	-	-	-	448.5
E	Hot Combustion Air to Burner No. 2	-	-	-	448.5

*See Figure 8 for stream identification codes and their relation to the Ketene Cooldown Heat Exchanger.

Table 21. Material balance for the ketene cooldown heat exchanger (SI units)

Basis: 1 hour of operation

Stream Code*	Stream Description	Ketene, kg	Water, kg	Acetic Acid, kg	Air, kg
A	Ketene/Acetic Acid from Ketene Furnace No. 23	317	136	109	-
B	Ketene/Acetic Acid to Quick Cooling Train	317	136	109	-
C	Ambient Air from Blower	-	-	-	407
D	Hot Combustion Air to Burner No. 1	-	-	-	203.5
E	Hot Combustion Air to Burner No. 2	-	-	-	203.5

*See Figure 8 for stream identification codes and their relation to the Ketene Cooldown Heat Exchanger.

Table 22. Energy balance for the ketene cooldown heat exchanger (English units)

Basis: 1 hour of operation

Stream Code*	Stream Description	Heat Added 1000 BTU/hr	source	Heat Removed 1000 BTU/hr	source
A	Ketene/Acetic Acid from Ketene Furnace No. 23	-	-	-	-
B	Ketene/Acetic Acid to Quick Cooling Train	-	-	293.2	air
C	Ambient Air from Blower	-	-	-	-
D	Hot Combustion Air to Burner No. 1	68.6	ketene	-	-
E	Hot Combustion Air to Burner No. 2	68.6	ketene	-	-
F	Radiation/Convection Heat Loss from Shell	-	-	(156.0)	shell loss
	Totals	137.2	-	137.2	-

*See Figure 8 for stream identification codes and their relation to the Ketene Cooldown Heat Exchanger.

Table 23. Energy balance for the ketene cooldown heat exchanger (SI units)

Basis: 1 hour of operation

Stream Code*	Stream Description	Heat Added kJ/s	Heat Added source	Heat Removed kJ/s	Heat Removed source
A	Ketene/Acetic Acid from Ketene Furnace No.23	-	-	-	-
B	Ketene/Acetic Acid to Quick Cooling Train	-	-	85.9	air
C	Ambient Air from Blower	-	-	-	-
D	Hot Combustion Air to Burner No. 1	20.1	ketene	-	-
E	Hot Combustion Air to Burner No. 2	20.1	ketene	-	-
F	Radiation/Convection Heat Loss From Shell	-	-	(45.7)	shell loss
	Totals	40.2	-	40.2	-

*See Figure 8 for stream identification codes and their relation to the Ketene Cooldown Heat Exchanger.

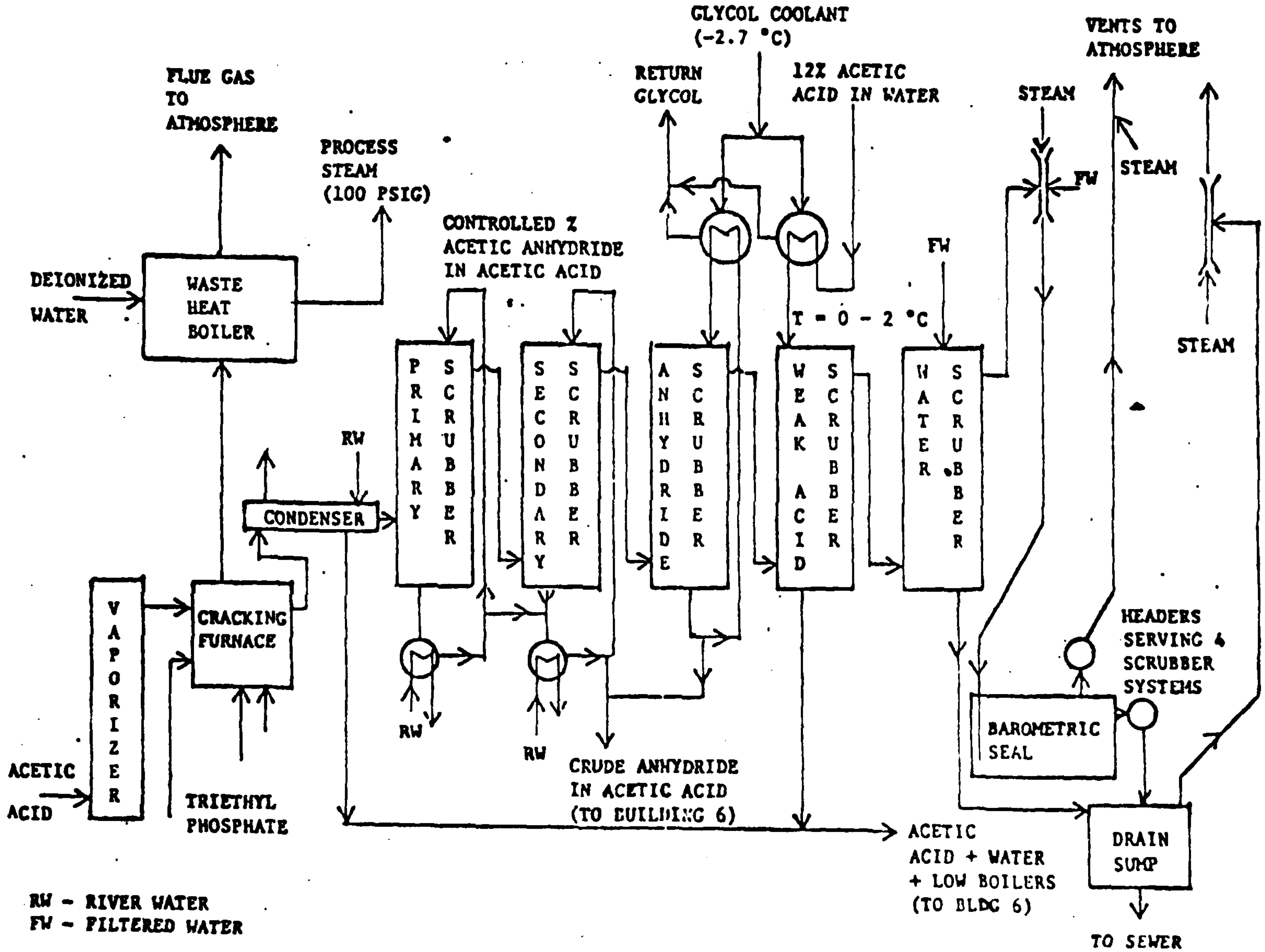


Figure 1. Flow diagram for the manufacture of crude acetic anhydride

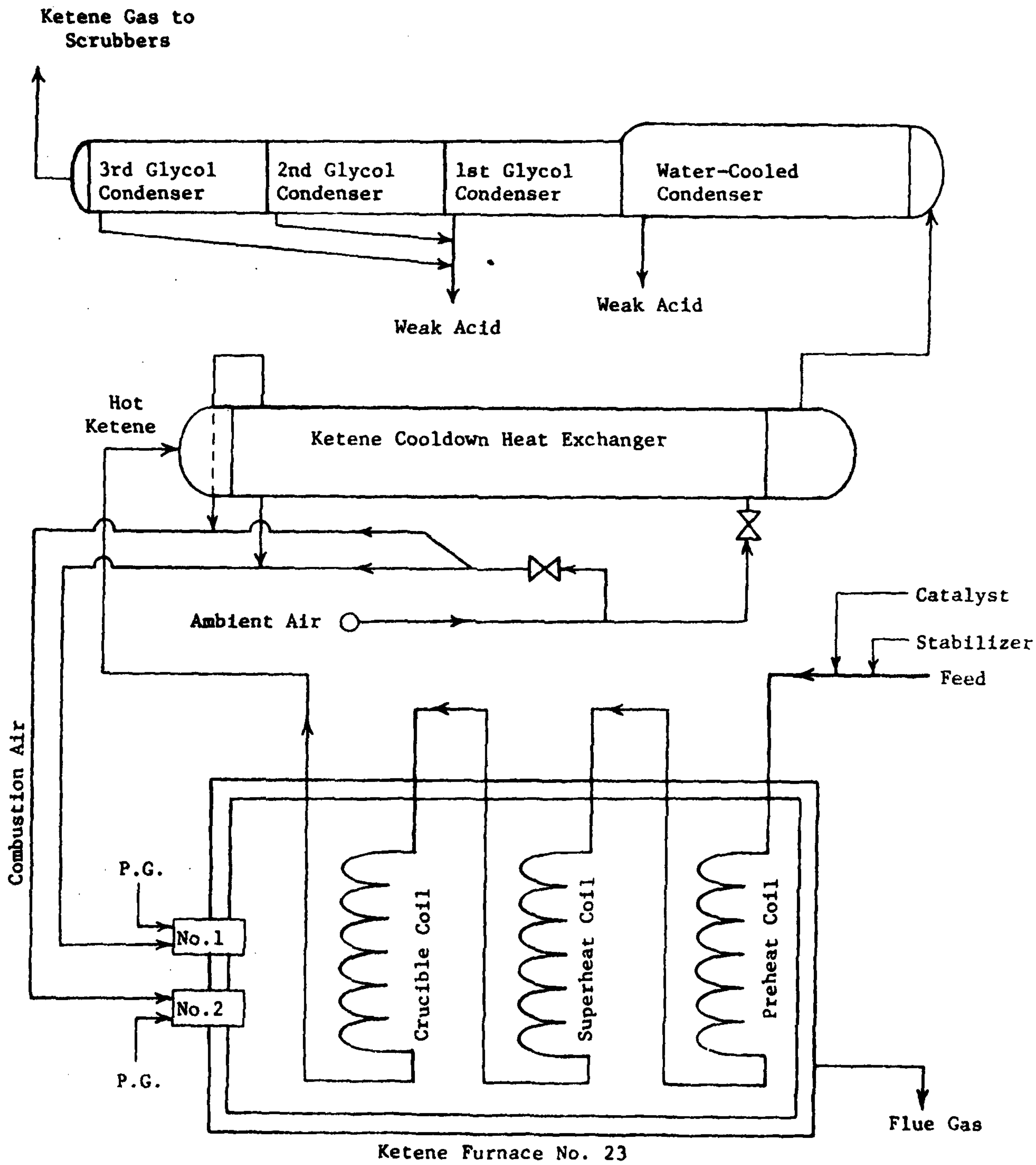
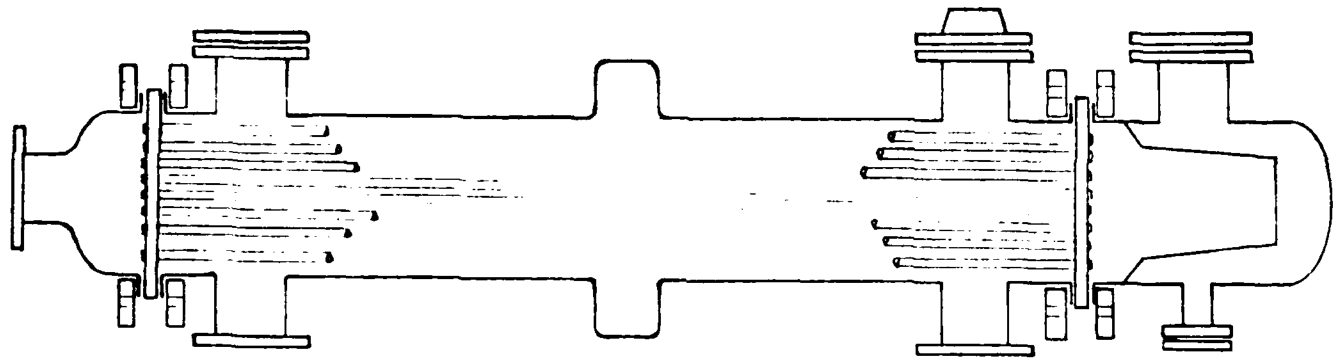


Figure 2. Flow diagram for ketene cooldown heat exchanger evaluation project



Tube Bundle:

Number of Tubes	-	91
Size	-	1" O.D. x #14 BWG x 10'6"
Material	-	304 S.S.
Surface Area	-	246 ft^2 (outside)
Working Pressure	-	110 psi
Other	-	Single Pass, tubes are rolled

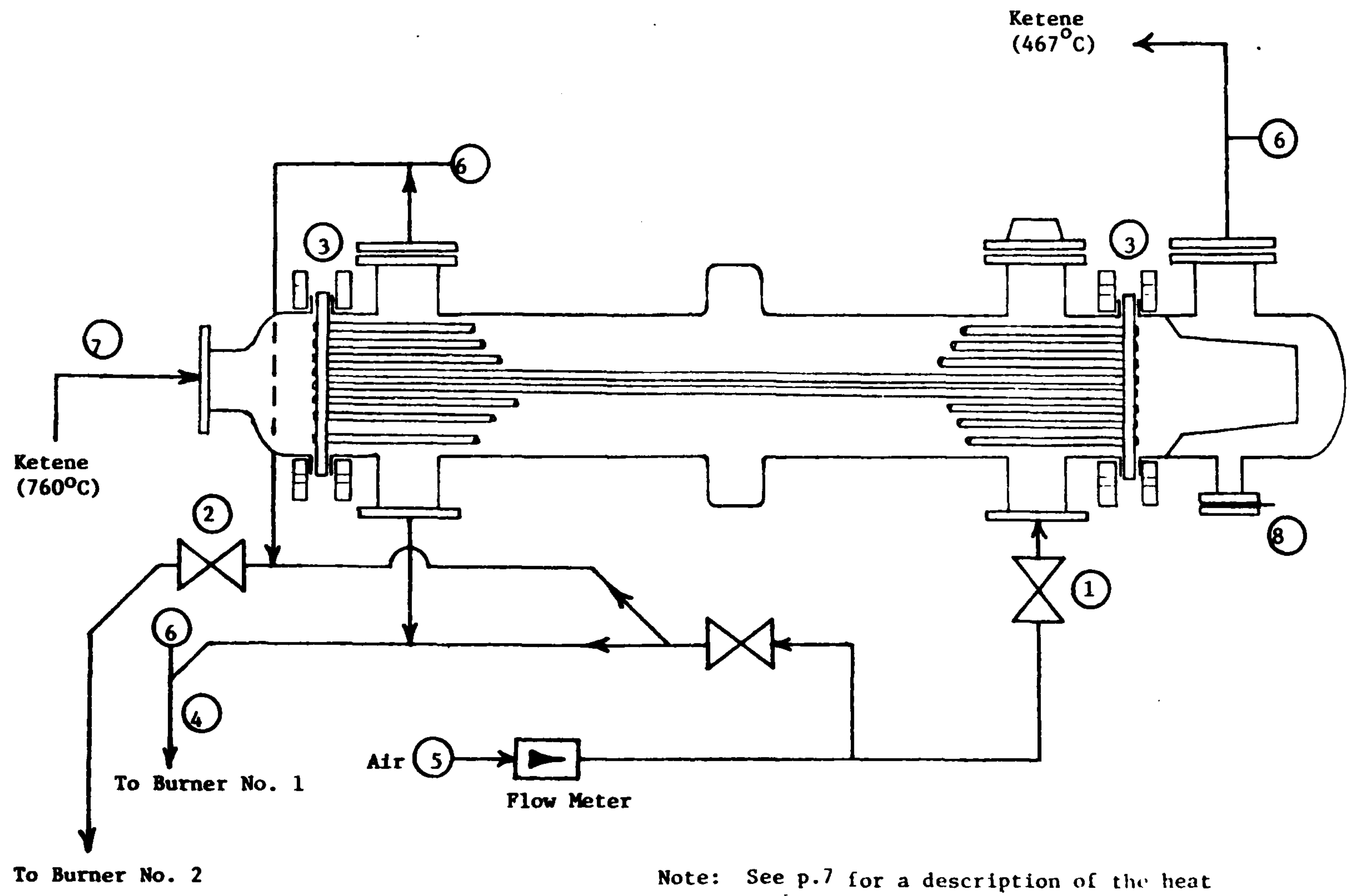
Shell:

Size	-	18" O.D. x 11'
Material	-	Carbon Steel
Working Pressure	-	50 psi
Other	-	Unbaffled, expansion joint equipped

Heads:

Material	-	430 S.S.
Gaskets (initial)	-	JM #61
(final)	-	PURPAK 2100
Working Pressure	-	110 psi

Figure 3. Heat exchanger construction data



Note: See p.7 for a description of the heat exchanger modifications.

Figure 4. Identification code for modifications of the ketene cooldown heat exchanger installation prior to restart of the evaluation

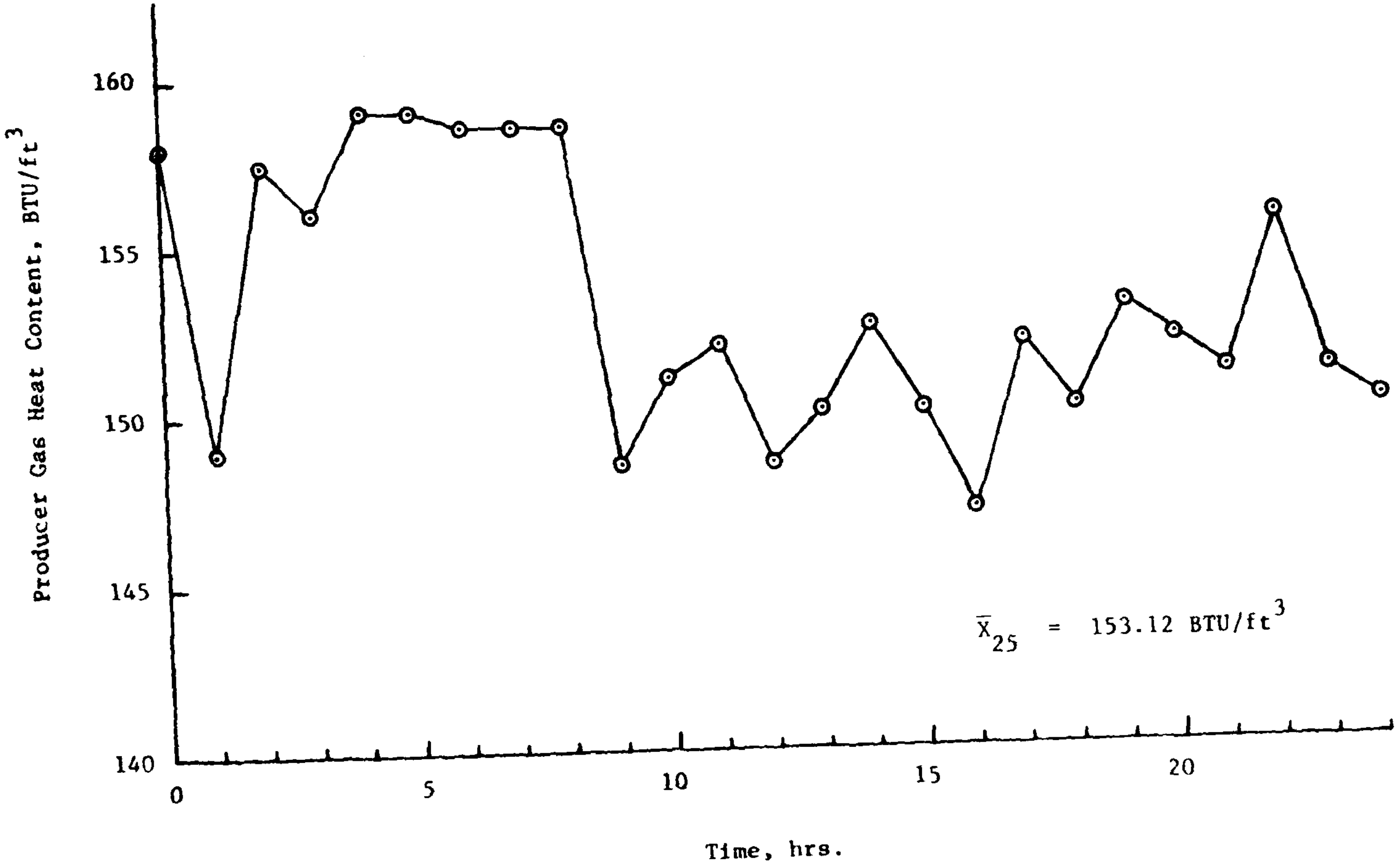


Figure 5. Heat content of producer gas manufactured at building 10A

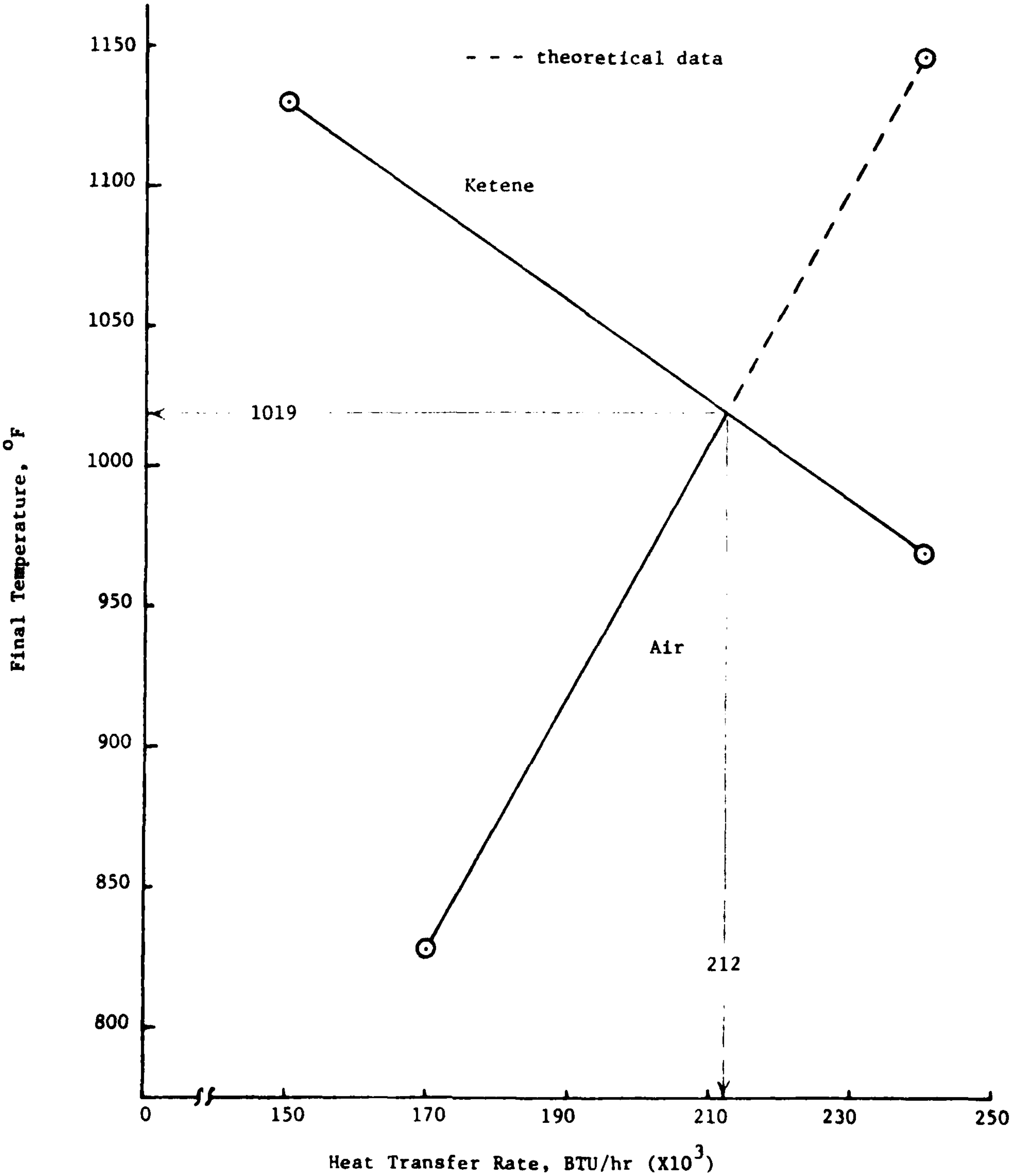


Figure 6. Graphical solution for determining maximum heat transfer rate and final stream temperature for combustion air at test no. 1 process conditions

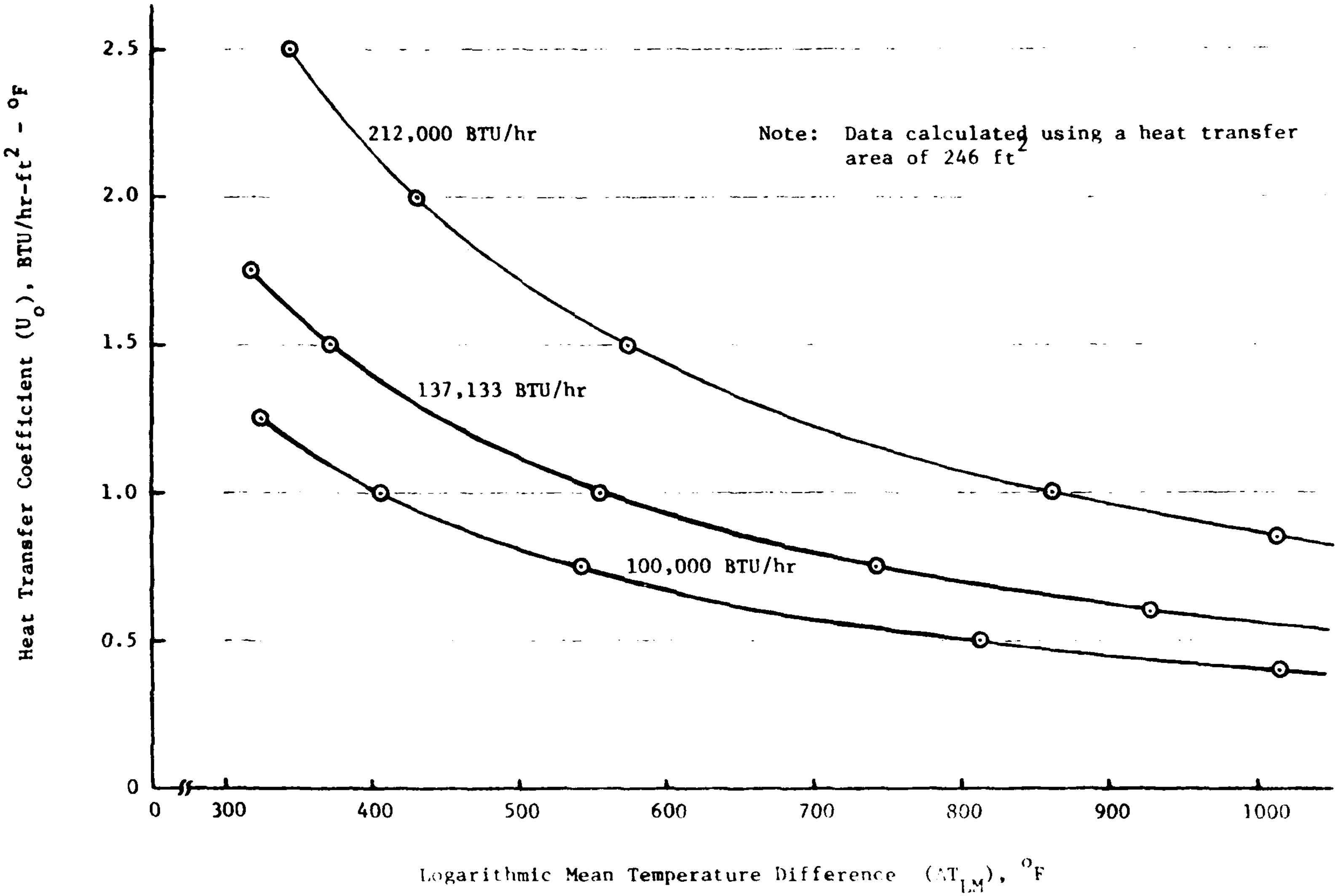


Figure 7. Variation of heat transfer coefficient with changes in logarithmic mean temperature difference at constant heat transfer rates of 212,000 BTU/hr, 137,133 BTU/hr, and 100,000 BTU/hr

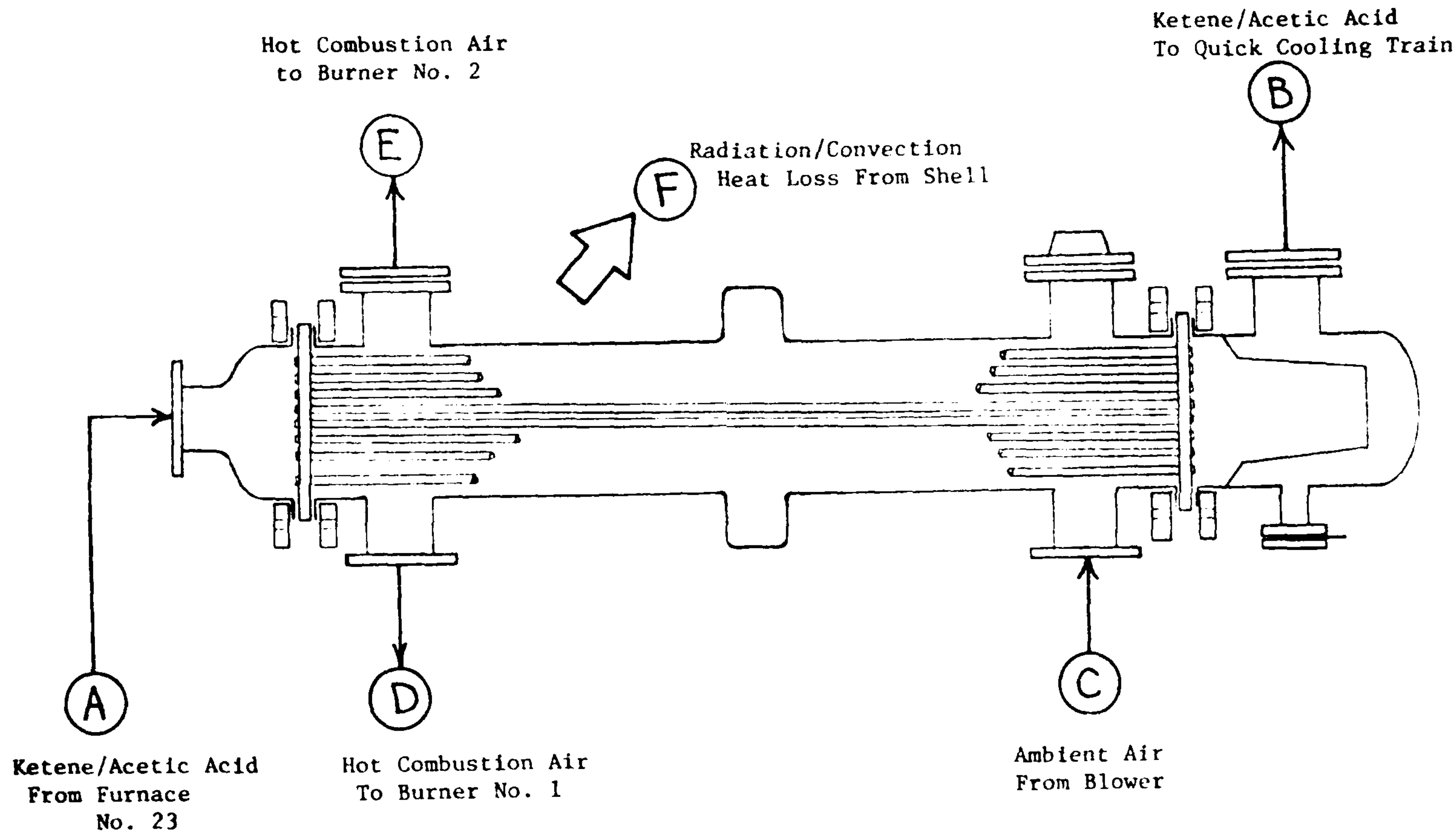


Figure 8. Stream identification code for material and energy balances for the ketene cooldown heat exchanger

APPENDIX A

CALCULATIONS FOR HEAT EXCHANGER OPERATION

CALCULATIONS FOR HEAT EXCHANGER OPERATION

I. Formulas Used in Calculations:

A. Gas Volume Correction for Change in Temperature (V_2)

$$V_2 = V_1 \times \frac{T_2}{T_1}$$

Where V_2 = final volume, ft^3

V_1 = initial volume, ft^3

T_2 = final temperature, ^oR

T_1 = initial temperature, ^oR

B. Quantity of Heat in Process Streams (Q)

$$Q = mCp\,(T_2 - T_1)$$

Where Q = quantity of heat, BTU

m = mass of substance, lbs

Cp = average heat capacity at constant pressure, BTU/lb - ^oF

T_2 = final temperature, ^oF

T_1 = initial temperature, ^oF

C. Logarithmic Mean Temperature Difference (ΔT_{LM})

$$\Delta T_{LM} = \frac{(T_{in} - t_{in}) - (T_{out} - t_{out})}{\ln\left(\dfrac{T_{in} - t_{in}}{T_{out} - t_{out}}\right)}$$

Where ΔT_{LM} = logarithmic mean temperature difference, ^oF

T_{in} = temperature of hot stream (in), ^oF

t_{in} = temperature of cold stream (in), ^oF

T_{out} = temperature of hot stream (out), ^oF

t_{out} = temperature of cold stream (out), ^oF

ln = natural logarithm

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D. Heat Transfer Coefficient (U)

$$q = UA\,\Delta T_{LM} \quad \text{or} \quad U = \frac{q}{A\,\Delta T_{LM}}$$

Where U = heat transfer coefficient, BTU/hr - ft^2 - ^oF

q = heat transferred, BTU/hr

A = heat exchange area, ft^2

ΔT_{LM} = logarithmic mean temperature difference, ^oF

II. Calculations for Heat Exchanger Operation During January 1982:

A. Process Data (See Tables 5 and 6)

1. Mass flow rate of ketene stream = 1,239 lbs/hr
2. Temperature of ketene into heat exchanger = 1,400^oF (760^oC)
3. Temperature of ketene out of heat exchanger = 873^oF (467^oC)
4. Volumetric flow rate of air stream - 193 ft^3/min
5. Temperature of air into heat exchanger = 54^oF (12^oC)
6. Temperature of air out of heat exchanger = 678^oF (359^oC)
7. Cp of air stream = 0.245 BTU/lb -^oF
8. Cp of ketene stream = 0.449 BTU/lb - ^oF
9. Mass of 1.0 lb - mole air at standard conditions (60^oF, 1 atm) = 29 lbs/lb-mole
10. Volume of 1.0 lb-mole air at standard conditions = 378.7 ft^3/lb-mole
11. Heat transfer area of heat exchanger = 246 ft^2
12. Producer Gas Usage = 355 ft^3/min

B. Mass Flow Rate of Air at Standard Conditions

1. Volume correction to standard conditions -

$$V_2 = V_1 \times \frac{T_2}{T_1}$$

$$V_2 = 193\ ft^3/min \times \frac{(60 + 460)^oR}{(54 + 460)^oR}$$

$$V_2 = 193\ ft^3/min \times \frac{(520)^oR}{(514)^oR}$$

$$V_2 = 195.3\ ft^3/min$$

2. Mass flow rate of air per hour -

$$m = 195.3\ ft^3/min \times 60\ min/hr \times \frac{1\ lb\text{-}mole\ air}{378.7\ ft^3} \times \frac{29\ lbs}{lb\text{-}mole\ air}$$

$$m = 897\ lbs/hr$$

C. Quantity of Heat Transferred to Air Stream

$$Q = mCp\ (T_2 - T_1)$$

$$Q = 897\ \text{lbs/hr} \times 0.245\ \frac{\text{BTU}}{\text{lb-}^{\circ}\text{F}} \times (678 - 54)^{\circ}\text{F}$$

$$Q = 137{,}133\ \text{BTU/hr}$$

D. Logarithmic Mean Temperature Difference

$$\Delta T_{LM} = \frac{(T_{in} - t_{in}) - (T_{out} - t_{out})}{\ln \frac{(T_{in} - t_{in})}{(T_{out} - t_{out})}}$$

$$\Delta T_{LM} = \frac{(1{,}400 - 54)^{\circ}\text{F} - (873\text{-}678)^{\circ}\text{F}}{\ln \frac{(1346)^{\circ}\text{F}}{(195)^{\circ}\text{F}}}$$

$$\Delta T_{LM} = \frac{(1346 - 195)^{\circ}\text{F}}{\ln(6.903)} = \frac{1151^{\circ}\text{F}}{1.932}$$

$$\Delta T_{LM} = 596^{\circ}\text{F}$$

E. Heat Transfer Coefficient of Heat Exchanger (shell side)

$$U = \frac{q}{A\ \Delta T_{LM}}$$

$$U = \frac{137{,}133\ \text{BTU/hr}}{(246\ \text{ft}^2)\ (596^{\circ}\text{F})}$$

$$U = 0.94\ \text{BTU/hr} - \text{ft}^2 - {}^{\circ}\text{F}$$

F. Apparent Heat Loss From Ketene Stream

$$Q = mCp\ (T_2 - T_1)$$

$$Q = 1{,}239\ \text{lbs/hr} \times 0.449\ \text{BTU/lb} - {}^{\circ}\text{F} \times (1{,}400 - 873)^{\circ}\text{F}$$

$$Q = 293{,}176\ \text{BTU/hr}$$

G. Calculated Producer Gas Reduction (PGR)

$$\text{PGR} = \frac{\text{heat saved}}{\text{heat content of PG}^{*}}$$

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*Average heat content value of producer gas (PG) is approximately 156 BTU/ft^3.

/

$$PGR = \frac{137{,}133 \text{ BTU/hr}}{156 \text{ BTU/ft}^{3*}}$$

$$PGR = 879 \text{ ft}^3\text{/hr}$$

$$PGR = 14.7 \text{ ft}^3\text{/min}$$

*Average heat content value of producer gas (PG) is approximately 156 BTU/ft^3.

H. Percertage of Reduction in Producer Gas (PG) Usage

$$\% \text{ Reduction} = \frac{14.7 \text{ ft}^3\text{/min}}{(355 + 14.7)\text{ft}^3\text{/min}} \times 100$$

$$\% \text{ Reduction} = \frac{14.7}{369.7} \times 100$$

$$\% \text{ Reduction} = 3.98\%$$

I. Estimated Annual Cost Savings Per Furnace

1. Heat saved per year -

$$Q = 137{,}133 \frac{\text{BTU}}{\text{hr}} \times 8{,}760 \frac{\text{hr}}{\text{yr}}$$

$$Q = 1.20 \times 10^9 \text{ BTU/yr}$$

2. Cost of Producer Gas (PG) per 10^6 BTU -

$$\text{Cost} = 10^6 \text{ BTU} \times \frac{1 \text{ ft}^3\text{(PG)}}{156 \text{ BTU}} \times \frac{\$.726}{10^3 \text{ ft}^3 \text{ (PG)}}$$

$$\text{Cost} = \$4.65/10^6 \text{ BTU}$$

3. Annual Cost Savings (CS) -

$$CS = 1.2 \times 10^9 \frac{\text{BTU}}{\text{yr}} \times \frac{\$4.65}{10^6 \text{ BTU}}$$

$$CS = \$5{,}580\text{/year}$$

III. Calculations for Heat Exchanger Operation During Test No. 2

A. Process Data (See Tables 8 and 9)

1. Mass flow rate of ketene stream = 1,240 lbs/hr
2. Temperature of ketene into heat exchanger = 1,393 ^{o}F (756 ^{o}C)
3. Temperature of ketene out of heat exchanger = 871 ^{o}F (466 ^{o}C)
4. Volumetric flow rate of air stream = 194 ft^3/min
5. Temperature of air into heat exchanger = 59 ^{o}F (15 ^{o}C)
6. Temperature of air out of heat exchanger = 678 ^{o}F (359 ^{o}C)
7. Cp of air stream = 0.245 BTU/lb - ^{o}F
8. Cp of ketene stream = 0.449 BTU/lb - ^{o}F
9. Mass of 1.0 lb-mole air at standard conditions (60 ^{o}F, 1 atm) = 29 lbs/lb-mole
10. Volume of 1.0 lb-mole air at standard conditions = 378.7 ft^3/lb-mole
11. Heat transfer area of heat exchanger = 246 ft^2
12. Producer Gas Usage = 362 ft^3/min

B. Mass Flow Rate of Air at Standard Conditions

1. Volume correction to standard conditions -

$$V_2 = V_1 \times \frac{T_2}{T_1}$$

$$V_2 = 194 \text{ ft}^3/\text{min} \times \frac{(60 + 460)^oR}{(59 + 460)^oR}$$

$$V_2 = 194 \text{ ft}^3/\text{min} \times \frac{(520)^oR}{(519)^oR}$$

$$V_2 = 194.4 \text{ ft}^3/\text{min}$$

2. Mass flow rate of air per hour -

$$m = 194.4 \text{ ft}^3/\text{min} \times 60 \frac{\text{min}}{\text{hr}} \times \frac{1 \text{ lb-mole air}}{378.7 \text{ ft}^3}$$

$$\times \frac{29 \text{ lbs}}{\text{lb-mole air}}$$

$$m = 893 \text{ lbs/hr}$$

C. Quantity of Heat Transferred to Air Stream

$$Q = m \, Cp \, (T_2 - T_1)$$

$$Q = 893 \frac{\text{lbs}}{\text{hr}} \times 0.245 \frac{\text{BTU}}{\text{lb}-^oF} \times (678-59)^oF$$

$$Q = 135,428 \text{ BTU/hr}$$

D. Logarithmic Mean Temperature Difference

$$\Delta T_{LM} = \frac{(T_{in} - t_{in})-(T_{out} - t_{out})}{\ln \frac{(T_{in}-t_{in})}{(T_{out}-t_{out})}}$$

$$\Delta T_{LM} = \frac{(1,393 - 59)^{o}F - (871 - 678)^{o}F}{\ln \frac{(1,334)^{o}F}{(193)^{o}F}}$$

$$\Delta T_{LM} = \frac{(1,334 - 193)^{o}F}{\ln 6.912} = \frac{1,141\ ^{o}F}{1.933}$$

$$\Delta T_{LM} = 590^{o}F$$

E. Heat Transfer Coefficient of Heat Exchanger (shell side)

$$U = \frac{q}{A\ \Delta T_{LM}}$$

$$U = \frac{135,428\ BTU/hr}{(246\ ft^2)\ (590^{o}F)}$$

$$U = 0.93\ BTU/hr - ft^2 -^{o}F$$

F. Apparent Heat Loss From Ketene Stream

$$Q = mCp\ (T_2 - T_1)$$

$$Q = 1,240\ lb/hr \times 0.449\ \frac{BTU}{lb-^{o}F} \times (1,393-871)\ ^{o}F$$

$$Q = 290,629\ BTU/hr$$

G. Calculated Producer Gas Reduction (PGR)

$$PGR = \frac{\text{heat saved}}{\text{heat content of PG*}}$$

$$PGR = \frac{135,428\ BTU/hr}{156\ BTU/ft^{3}*}$$

$$PGR = 868\ ft^3/hr$$

$$PGR = 14.5\ ft^3/min$$

*Average heat content value of producer gas (PG) is approximately 156 BTU/ft^3.

H. Percentage of Reduction in Producer Gas (PG) Usage

$$\% \text{ Reduction} = \frac{14.5 \text{ ft}^3/\text{min}}{(362 + 14.5) \text{ ft}^3/\text{min}} \times 100$$

$$\% \text{ Reduction} = \frac{14.5}{376.5} \times 100$$

$$\% \text{ Reduction} = 3.85\%$$

I. Estimated Annual Cost Savings Per Furnace

1. Heat saved per year -

$$Q = 135{,}428 \frac{\text{BTU}}{\text{hr}} \times 8{,}760 \frac{\text{hr}}{\text{yr}}$$

$$Q = 1.19 \times 10^9 \text{ BTU/yr}$$

2. Cost of Producer Gas (PG) per 10^6 BTU -

$$\text{Cost} = 10^6 \text{ BTU} \times \frac{1 \text{ ft}^3\text{(PG)}}{156 \text{ BTU}} \times \frac{\$.726}{10^3 \text{ ft}^3\text{(PG)}}$$

$$\text{Cost} = \$4.65/10^6 \text{ BTU}$$

3. Annual Cost Savings (CS) -

$$CS = 1.19 \times 10^9 \frac{\text{BTU}}{\text{yr}} \times \frac{\$4.65}{10^6 \text{BTU}}$$

$$CS = \$5{,}534/\text{year}$$

IV. Calculations for Heat Exchanger Operation During Test No. 3

A. Process Data (See Tables 11 and 12)

1. Mass flow rate of ketene stream = 1,239 lbs/hr
2. Temperature of ketene into heat exchanger = 1,396°F (758°C)
3. Temperature of ketene out of heat exchanger = 874°F (468°C)
4. Volumetric flow rate of air stream = 195 ft^3/min
5. Temperature of air into heat exchanger = 64°F (18°C)
6. Temperature of air out of heat exchanger = 680°F (360°C)
7. Cp of air stream = 0.245 BTU/lb-°F
8. Cp of ketene stream - 0.449 BTU/lb-°F
9. Mass of 1.0 lb-mole air at standard conditions (60°F, 1 atm) = 29 lbs/lb-mole
10. Volume of 1.0 lb-mole air at standard conditions = 378.7 ft^3/lb-mole
11. Heat transfer area of heat exchanger = 246 ft^2
12. Producer Gas Usage = 370 ft^3/min

B. Mass Flow Rate of Air at Standard Conditions

1. Volume correction to standard conditions-

$$V_2 = V_1 \times \frac{T_2}{T_1}$$

$$V_2 = 195 \text{ ft}^3/\text{min} \times \frac{(60 + 460)^{\circ}R}{(64 + 460)^{\circ}R}$$

$$V_2 = 195 \text{ ft}^3/\text{min} \times \frac{(520)^{\circ}R}{(524)^{\circ}R}$$

$$V_2 = 193.5 \text{ ft}^3/\text{min}$$

2. Mass flow rate of air per hour -

$$m = 193.5 \text{ ft}^3/\text{min} \times 60 \frac{\text{min}}{\text{hr}} \times \frac{1 \text{ lb-mole air}}{378.7 \text{ ft}^3} \times \frac{29 \text{ lbs}}{\text{lb-mole air}}$$

$$m = 899 \text{ lbs/hr}$$

C. Quantity of Heat Transferred to Air Stream

$$Q = mCp\ (T_2 - T_1)$$

$$Q = 889 \frac{\text{lbs}}{\text{hr}} \times 0.245 \frac{\text{BTU}}{\text{lb-}^{\circ}\text{F}} \times (680\text{-}64)\ ^{\circ}\text{F}$$

$$Q = 134{,}168 \text{ BTU/hr}$$

D. Logarithmic Mean Temperature Difference

$$\Delta T_{LM} = \frac{(T_{in} - t_{in}) - (T_{out} - t_{out})}{\ln \frac{(T_{in} - t_{in})}{(T_{out} - t_{out})}}$$

$$\Delta T_{LM} = \frac{(1{,}396\text{-}64)^{\circ}F - (874\text{-}680)^{\circ}F}{\ln \frac{(1{,}332)^{\circ}F}{(194)^{\circ}F}}$$

$$\Delta T_{LM} = \frac{(1{,}332\text{-}194)^{\circ}F}{\ln 6.866} = \frac{1{,}138}{1.927}$$

$$\Delta T_{LM} = 591^{\circ}F$$

E. Heat Transfer Coefficient of Heat Exchanger (shell side)

$$U = \frac{q}{A\ \Delta T_{LM}}$$

$$U = \frac{134{,}168\ \text{BTU/hr}}{(246\ \text{ft}^2)\ (591^\circ\text{F})}$$

$$U = 0.92\ \text{BTU/hr-ft}^2\text{-}^\circ\text{F}$$

F. Apparent Heat Loss From Ketene Stream

$$Q = mCp(T_2 - T_1)$$

$$Q = 1{,}239\ \text{lb/hr} \times 0.449\ \frac{\text{BTU}}{\text{lb-}^\circ\text{F}} \times (1{,}396-874)^\circ\text{F}$$

$$Q = 290{,}394\ \text{BTU/hr}$$

G. Calculated Producer Gas Reduction (PGR)

$$PGR = \frac{\text{heat saved}}{\text{Heat content of PG*}}$$

$$PGR = \frac{134{,}168\ \text{BTU/hr}}{156\ \text{BTU/ft}^3\text{*}}$$

$$PGR = 860\ \text{ft}^3\text{/hr}$$

$$PGR = 14.3\ \text{ft}^3\text{/min}$$

*Average heat content value of producer gas (PG) is approximately 156 BTU/ft^3.

H. Percentage of Reduction in Producer Gas (PG) Usage

$$\%\ \text{Reduction} = \frac{14.3\ \text{ft}^3\text{/min}}{(370 + 14.3)\ \text{ft}^3\text{/min}} \times 100$$

$$\%\ \text{Reduction} = \frac{14.3}{384.3} \times 100$$

$$\%\ \text{Reduction} = 3.72\%$$

I. Estimated Annual Cost Savings Per Furnace

1. Heat saved per year-

$$Q = 134{,}168\ \text{BTU/hr} \times 8{,}760\ \frac{\text{hr}}{\text{yr}}$$

$$Q = 1.18 \times 10^9 \text{ BTU/yr}$$

2. Cost of Producer Gas (PG) per 10^6 BTU -

$$\text{Cost} = 10^6 \text{ BTU} \times \frac{1 \text{ ft}^3\text{(PG)}}{156 \text{ BTU}} \times \frac{\$.726}{10^3 \text{ ft}^3\text{(PG)}}$$

$$\text{Cost} = \$4.65/10^6 \text{ BTU}$$

3. Annual Cost Savings (CS) -

$$CS = 1.18 \times 10^9 \frac{\text{BTU}}{\text{yr}} \times \frac{\$4.65}{10^6 \text{ BTU}}$$

$$CS = \$5{,}487/\text{year}$$

V. Calculations for Heat Exchanger Operation Test No. 2: 25th Day

A. Process Data

1. Mass flow rate of ketene stream = 1,240 lbs/hr
2. Temperature of ketene into heat exchanger = 1,395°F(757°C)
3. Temperature of ketene out of heat exchanger = 873°F (467°C)
4. Volumetric flow rate of air stream = 188 ft^3/min
5. Temperature of air into heat exchanger = 57°F (14°C)
6. Temperature of air out of heat exchanger = 680°F (360°C)
7. Cp of air stream = 0.245 BTU/lb-°F
8. Cp of ketene stream = 0.449 BTU/lb-°F
9. Mass of 1.0 lb-mole of air at standard conditions (60°F, 1 atm) = 29 lbs/lb-mole
10. Volume of 1.0 lb-mole of air at standard conditions = 378.7 ft^3/lb-mole
11. Heat transfer area of heat exchanger = 246 ft^2
12. Producer Gas Usage = 354 ft^3/min
13. Heat content of PG on February 25, 1982 = 153.12 BTU/ft^3

B. Mass Flow Rate of Air at Standard Conditions

1. Volume correction to standard conditions-

$$V_2 = V_1 \times \frac{T_2}{T_1}$$

$$V_2 = 188 \text{ ft}^3/\text{min} \times \frac{(60 + 460)^\circ R}{(57 + 460)^\circ R}$$

$$V_2 = 188 \text{ ft}^3/\text{min} \times \frac{(520)^\circ R}{(517)^\circ R}$$

$$V_2 = 189.1 \text{ ft}^3/\text{min}$$

2. Mass flow rate of air per hour -

$$m = 189.1\ ft^3/min \times 60\ min/hr \times \frac{1\ lb\text{-}mole\ air}{378.7\ ft^3} \times \frac{29\ lbs}{lb\text{-}mole\ air}$$

$$m = 869\ lbs/hr$$

C. Quantity of Heat Transferred to Air Stream

$$Q = mCp\ (T_2 - T_1)$$

$$Q = 869\ \frac{lbs}{hr} \times 0.245\ \frac{BTU}{lb\text{-}^oF} \times (680-57)\ ^oF$$

$$Q = 132{,}640\ BTU/hr$$

D. Logarithmic Mean Temperature Difference

$$\Delta T_{LM} = \frac{(T_{in} - t_{in}) - (T_{out} - t_{out})}{\ln \frac{(T_{in} - t_{in})}{(T_{out} - t_{out})}}$$

$$\Delta T_{LM} = \frac{(1{,}395-57)^oF - (873-680)^oF}{\ln \frac{(1{,}338)^oF}{(193)^oF}}$$

$$\Delta T_{LM} = \frac{(1{,}338 - 193)^oF}{\ln 6.933} = \frac{1{,}145^oF}{1.936}$$

$$\Delta T_{LM} = 591^oF$$

E. Heat Transfer Coefficient of Heat Exchanger (shell side)

$$U = \frac{q}{A\ \Delta T_{LM}}$$

$$U = \frac{132{,}640\ BTU/hr}{(246\ ft^2)\ (591^oF)}$$

$$U = 0.91\ BTU/hr\text{-}ft^2\text{-}^oF$$

F. Apparent Heat Loss From Ketene Stream

$$Q = mCp\ (T_2 - T_1)$$

$$Q = 1{,}240\ lb/hr \times 0.449\ BTU/lb\text{-}^oF \times (1{,}395-873)^oF$$

$$Q = 290{,}629\ BTU/hr$$

G. Calculated Producer Gas Reduction (PGR)

$$PGR = \frac{\text{heat saved}}{\text{heat content of PG}}$$

$$PGR = \frac{132{,}640 \text{ BTU/hr}}{153.12 \text{ BTU/ft}^3}$$

$$PGR = 866 \text{ ft}^3\text{/hr}$$

$$PGR = 14.4 \text{ ft}^3\text{/min}$$

H. Percentage of Reduction in Producer Gas (PG) Usage

$$\% \text{ Reduction} = \frac{14.4 \text{ ft}^3\text{/min}}{(354 + 14.4) \text{ ft}^3\text{/min}} \times 100$$

$$\% \text{ Reduction} = \frac{14.4}{368.4} \times 100$$

$$\% \text{ Reduction} = 3.91\%$$

I. Estimated Annual Cost Savings Per Furnace

1. Heat saved per year -

$$Q = 132{,}640 \text{ BTU/hr} \times 8{,}760 \text{ hr/yr}$$

$$Q = 1.16 \times 10^9 \text{BTU/yr}$$

2. Cost of Producer Gas (PG) per 10^6BTU -

$$\text{Cost} = 10^6\text{BTU} \times \frac{1 \text{ ft}^3\text{(PG)}}{153.12 \text{ BTU}} \times \frac{\$.726}{10^3\text{ft}^3\text{(PG)}}$$

$$\text{Cost} = \$4.74/10^6\text{BTU}$$

3. Annual Cost Savings (CS) -

$$CS = 1.16 \times 10^9 \frac{\text{BTU}}{\text{yr}} \times \frac{\$4.74}{10^6 \text{ BTU}}$$

$$CS = \$5{,}498\text{/year}$$

VI. Calculations for Operating Conditions During Test No. 2: 5th - 12th Days When Heat Exchanger Was Not Used to Preheat Combustion Air:

A. Process Data (See Tables 8 and 9)

1. Mass flow rate of ketene stream = 1,240 lbs/hr
2. Temperature of ketene into heat exchanger = 1,398°F (759°C)
3. Temperature of ketene out of heat exchanger = 1,002°F (539°C)
4. Cp of ketene stream = 0.449 BTU/lb - °F
5. Volumetric flow rate of air stream = 192 ft^3/min
6. Temperature of combustion air = 54°F (12°C)

7. Producer Gas Usage (Without Air Preheat) = 379 ft^3/min
8. Producer Gas Usage (With Air Preheat) = 362 ft^3/min

B. Apparent Heat Loss From Ketene Stream

$$Q = mCp\ (T_2 - T_1)$$

$$Q = 1{,}240\ \text{lbs/hr} \times 0.449\ \frac{\text{BTU}}{\text{lb-}^{o}\text{F}} \times (1{,}398 - 1{,}002)\ ^{o}\text{F}$$

$$Q = 220{,}477\ \text{BTU/hr}$$

C. Apparent Producer Gas Usage Increase Without Preheat of Combustion Air

$$\text{PG Increase} = (379 - 362)\ \text{ft}^3/\text{min}$$

$$\text{PG Increase} = 17.0\ \text{ft}^3/\text{min}$$

D. Percentage of Increase in Producer Gas (PG) Usage

$$\%\ \text{Increase} = \frac{17.0\ \text{ft}^3/\text{min}}{(362 + 17)\ \text{ft}^3/\text{min}} \times 100$$

$$\%\ \text{Increase} = \frac{17.0}{379.0} \times 100$$

$$\%\ \text{Increase} = 4.49\%$$

E. Estimated Annual Cost Increase Per Furnace

1. Heat increase per year -

$$Q = 17.0\ \frac{\text{ft}^3}{\text{min}} \times \frac{156\ \text{BTU*}}{\text{ft}^3} \times 60\ \frac{\text{min}}{\text{hr}} \times 8{,}760\ \frac{\text{hr}}{\text{yr}}$$

$$Q = 1.39 \times 10^9\ \text{BTU/yr}$$

2. Cost of Producer Gas (PG) per 10^6 BTU -

$$\text{Cost} = 10^6\text{BTU} \times \frac{1\ \text{ft}^3\text{(PG)*}}{156\ \text{BTU}} \times \frac{\$.726}{10^3\ \text{ft}^3\text{(PG)}}$$

$$\text{Cost} = \$4.65/10^6\ \text{BTU}$$

3. Annual Cost Increase (CI)-

$$\text{CI} = 1.39 \times 10^9\frac{\text{BTU}}{\text{yr}} \times \frac{\$4.65}{10^6\ \text{BTU}}$$

$$\text{CI} = \$6{,}464/\text{year}$$

*Average heat content value of producer gas (PG) is approximately 156 BTU/ft^3.

APPENDIX B

THEORETICAL OXYGEN REQUIRED TO BURN PRODUCER GAS

MANUFACTURED AT HSAAP ON 25TH DAY OF TEST NO. 2

I. Producer Gas Analysis (Basis: 1.0 mole)*:

Component	Volume %	Molecular Weight	Weight, lbs/mole	Weight Fraction
H_2	18.96	2	0.38	0.016
O_2	0.77	32	0.25	0.011
N_2	51.11	28	14.31	0.599
CH_4	2.04	16	0.33	0.014
CO	20.50	28	5.74	0.240
CO_2	6.32	44	2.78	0.116
C_2H_4	0.24	28	0.07	0.003
C_2H_6	0.06	30	0.02	0.001
Totals	100.00	-	23.88	1.000

*Heat content of producer gas with this analysis is 153.12 BTU/ft^3.
A pound mole of producer gas weighs approximately 23.88 pounds.

II. Chemical Equations for Combustion of the Combustible Components of Producer Gas:

A. $H_2 + 0.5\ O_2 \rightarrow H_2O$

B. $CH_4 + 2.0\ O_2 \rightarrow CO_2 + H_2O$

C. $CO + 0.5\ O_2 \rightarrow CO_2$

D. $C_2H_4 + 3.0\ O_2 \rightarrow 2.0\ CO_2 + 2.0\ H_2O$

E. $C_2H_6 + 3.5\ O_2 \rightarrow 2.0\ CO_2 + 3.0\ H_2O$

III. Theoretical Oxygen Requirement:

Volumetric Calculations:

Basis: 1.0 mole Producer Gas (PG)

Component	Moles	Mole Ratio (Comp.: O_2)	Theoretical Moles O_2
H_2	0.1896	0.5	0.0948
CH_4	0.0204	2.0	0.0408
CO	0.2050	0.5	0.1025
C_2H_4	0.0024	3.0	0.0072
C_2H_6	0.0006	3.5	0.0021
Totals	0.4180	-	0.2474**

**This figure must be corrected (reduced) to account for the oxygen content of the producer gas. In this case, the additional oxygen required for theoretical combustion is the quantity of oxygen being sought.

$$\text{Additional Oxygen Needed} = \text{Total } O_2 - O_2 \text{ in Producer Gas}$$

$$= (0.2474 - 0.0077) \text{ moles } O_2/\text{mole PG}$$

$$= 0.2397 \text{ moles } O_2/\text{mole PG}$$

IV. Combustion Air Requirement (Theoretical):

A. Volume of Air at Standard Conditions (60°F, 1 atm) -

$$\text{Vol. of Air} = \frac{0.2397 \text{ moles } O_2}{\text{mole PG}} \times \frac{1 \text{ mole air}}{0.21 \text{ moles } O_2}$$

$$\text{Vol. of Air} = 1.141 \text{ moles air/mole PG}$$

$$= 1.141 \text{ ft}^3 \text{ air/ft}^3 \text{ of PG}$$

B. Weight Ratio of Air to Producer Gas (PG) -

$$\text{Weight Ratio} = \frac{1.141(29)}{1\ (23.88)}$$

$$\text{Weight Ratio} = \frac{33.09}{23.88}$$

$$\text{Weight Ratio} = 1.386 \text{ lbs air/lb of PG}$$

APPENDIX C

ECONOMIC EVALUATION

ECONOMIC EVALUATION*

I. Cost of Heat Exchanger Process Equipment and Installation (per furnace):

A. Heat Exchanger (246 ft^2, Type BEM)

1.	Base Price, $P = 125\ (18)^{1.037}$	$2,504	
2.	Shell	704	
3.	Expansion Joint	335	
4.	Nozzles	90[illegible]	
5.	Tubes	118	
6.	Tubes Material Correction (304SS)	1,697	
7.	Support Plates	100	
8.	ASME Code Stamp, etc.	130	
	Base Cost	$6,493	
	+Installation Cost (25%)	1,623	
		$8,116	
	+ Cost Adjustment from 1977 estimate (49%)	$3,984	
		$12,100	$12,100

B. Instruments, Valves, and Installation Materials

1.	4-Point Temperature Transmitter/Recorder (1)	$ 2,250	
2.	Flow Transmitter/Recorder (1)	1,750	
3.	5-inch Butterfly Valves (2)	900	
4.	Piping, elbows, etc.	2,550	
5.	Insulation	200	
6.	Miscellaneous Installation Materials	400	
		$ 8,050	$ 8,050

C. Labor

1.	Fabrication (240 hrs.)	$ 9,600	
2.	Installation (excluding Heat Exchanger)(80hrs)	3,200	
3.	Electrical (40 hrs.)	1,600	
		$14,400	$14,400
	TOTAL COST		$34,550

II. Cost Savings Calculations (per furnace):

A. On Basis of Best Operating Data During Evaluation (Test No. 1)

1. Heat Saved (See Calculations for Heat Exchanger Operation in January 1982, pp 52-54) -

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* 1982 dollars.

$Q = 137,133$ BTU/hr

$Q = 137,133 \text{ BTU/hr} \times 8,760 \text{ hrs/yr} = 1.2 \times 10^9 \text{ BTU/yr}$

2. Cost of Producer Gas per 10^6 BTU's -

$$\text{Cost} = 10^6 \text{ BTU} \times \frac{1 \text{ ft}^3}{156 \text{ BTU}} \times \frac{\$.726}{10^3 \text{ ft}^3}$$

$$= \$4.65/10^6 \text{ BTU}$$

3. Cost Savings (one furnace - one year) -

$$\text{Savings} = 1.2 \times 10^9 \text{ BTU/yr} \times \$4.65/10^6 \text{ BTU}$$

$$= \underline{\underline{\$5,580/\text{year}}}$$

III. Profitability Index (PI) and Payback Calculations:

A. Current Operational Level (5 Furnaces) -

Note: To fully realize the calculated cost savings of $5,580/year for each of the 5 ketene furnaces being used at the current operational level, all furnaces within the operating quadrant (8 furnaces) must be equipped with heat recovery systems to compensate for the service rotation between furnaces during the payback period that is associated with maintenance of the furnaces and their cooling/scrubbing systems. As a result, the PI and Payback calculations for the 5-Furnace (current) operational level reflect cost savings for 5 furnaces and implementation costs for 8 furnaces.

1. $$\text{PI} = \frac{\text{Annual Cost Savings } (6.447)^*}{\text{Cost to Implement Project}}$$

$$\text{PI} = \frac{\$27,900 \ (6.447)}{\$276,400} = \frac{\$179,871}{\$276,400}$$

$$\text{PI} = 0.651$$

* Present Worth Factor, 10%-10 years

2. $$\text{Payback Period} = \frac{\text{Cost to Implement Project}}{\text{Annual Cost Savings}}$$

$$\text{Payback Period} = \frac{\$276,400}{\$27,900/\text{year}}$$

$$\text{Payback Period} = 9.9 \text{ years}$$

B. Mobilization Operational Level (46 Furnaces) -

Note: Because of the 96% service factor for furnace operations, heat exchangers would have to be installed on all 48 furnaces but only 46 furnaces would operate at any given time. The cost savings calculations below reflect this fact.

1. $PI = \frac{\text{Annual Cost Savings (6.447)*}}{\text{Cost to Implement Project}}$

$$= \frac{\$256,680\ (6.447)}{\$1,658,400} = \frac{\$1,654,816}{\$1,658,400}$$

$$= 0.998$$

*Present Worth Factor, 10%, 10 years

2. $\text{Payback Period} = \frac{\text{Cost to Implement Project}}{\text{Annual Cost Savings}}$

$$= \frac{\$1,658,400}{\$256,680}$$

$$= 6.5 \text{ years}$$

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